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THE INFLUENCE OF RAMP SPACING ON THE TRAFFIC FLOW CHARACTERISTICS ON THE ATLANTA FREEWAY SYSTEM

A THESIS

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CHAPTER I

INTRODUCTION

The spacing and location of interchanges on a freeway may have a pronounced effect on its effective operation. Since freeways are a very important link in the overall transportation system of the city, the location and spacing of interchanges may influence the operation of the entire highway transportation system of the city.

In the freeway system, interchanges which are spaced too far apart may not permit the full potential use of the freeway, nor allow the freeway to provide the necessary service. However, interchanges which are located too close together may result in inefficiency and loss of capacity on the freeway. Studies also indicate that the factors having the greatest effect on freeway operation are the design and operation of ramps and interchanges (1)*.

Estimates for 1980 indicate there will be a need for 16,000 miles of freeways to serve urban traffic within urban areas (2). One of the major portions of the cost of these freeways will be the interchanges. Since the cost of these interchanges is extremely high, their spacing becomes important from the viewpoint of cost. Any interchange which is built without sufficient economic justification may add unnecessarily to the cost of the freeway. However, the lack of an interchange

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*Numbers in parentheses refer to references listed in the Bibliography.

in the proper location can destroy the effective operation of the entire freeway.

Purpose

The purpose of this study is to determine the influence of ramp spacing upon the traffic flow characteristics on the Atlanta Freeway System. Investigation of traffic speed, volume, and density of flow were made at various locations on the freeway system under conditions of variable ramp spacings. Speed and delay studies were also made on the freeway to determine the total overall travel time of all the vehicles using the freeway during the afternoon peak hour under conditions of variable ramp spacing.

In carrying out a study of this type, two different approaches could be used to study the influence of ramp spacing on traffic in a freeway and surface street system. One method would be the microscopic concept in which the study would be confined to determining the influence of ramp spacing on the traffic flow characteristics on the freeway alone and disregarding the changes which take place on the surface streets which serve the freeway. The second would be the system concept in which the study would be enlarged to consider not only the operation of the freeway, but also the surface streets which serve the freeway.

The data presented in this thesis were collected on a study now being conducted by the Georgia Tech Engineering Experiment Station on the North Freeway in Atlanta.* This study uses the system concept to

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*Project HPS-1 (59), Georgia Tech Engineering Experiment Station, "The Influence of Ramp Spacing on the Traffic Flow Characteristics on the Atlanta Freeway System."

determine the influence of ramp spacing on the entire system of surface streets and freeway. This thesis shall be confined to determining the influence of ramp spacing on the traffic flow characteristics on the freeway only, and will not consider the operation of the system.

Literature Research

Studies of the operational characteristics of freeways under conditions of variable ramp spacing have not been made to any extent. Limited studies have been made to determine the effect of closing ramps on the operational characteristics of the freeway in the vicinity of the ramp which has been closed.

In Seattle, Washington, access to Lake Way, a limited access facility, was controlled by the closure of three on-ramps during selected peak traffic periods (3). This program was started in January, 1960, and has continued to date, with the on-ramps being closed from 7 to 9 A. M. and from 4 to 6 P. M. As a result of the ramp closure operation, data indicated average speeds were increased by five miles per hour and the records indicated a significant reduction in accidents. Limited studies indicated a smoother, less hazardous operation after ramp closure. One significant factor was the excellent public acceptance of the ramp closure program.

Studies were carried out on the Gulf Freeway in Houston and the Central Expressway in Dallas to determine the effect of eliminating the "short trip" from the freeways in the vicinity of the Central Business District (4). These studies were carried out by closing all inbound

on-ramp during the morning peak hour for a distance of approximately one and one-quarter miles from the Central Business District. The studies show that volume control is feasible and practical to improve operational efficiency on existing freeways, where adequate capacity is available on parallel facilities such as continuous frontage roads or major streets (5). These studies also indicated that volume control is necessary only for a period of less than one hour during the peak period of traffic flow. During the balance of the day there should be no control to allow the maximum benefit to short trip users of the freeway.

Criteria for Spacing of Interchanges

There are two major factors which influence the location and spacing of interchanges on a freeway. These are external factors such as size of city, type of area, and street pattern, and internal factors, such as geometric features and operational characteristics of the freeway (6).

External Factors

When the street pattern of the area which the freeway serves is regular, such as the familiar gridiron pattern, the need for closely spaced interchanges is reduced. This consideration is especially true when the freeway parallels one set of streets and has continuous frontage roads. However, a hetrogeneous or a disconnected pattern of streets together with an irregular arterial street system may tend to require closer spacing of interchanges than might otherwise be desirable.

The land use patterns of the area will influence the spacing of the interchanges to a considerable extent. Large traffic generating

areas such as large commercial and industrial areas will usually call for numerous points of ingress and egress and outlying residential areas will not require as many closely spaced interchanges.

Many times the area through which the freeway is being built is an urban revewal area and it may be desirable to locate interchanges in certain areas because of low land cost. When freeways are constructed as a portion of an urban renewal program one may desire to influence the redevelopment of certain areas to commercial, industrial, or residential land uses. This particular consideration will influence both the type and spacing of interchanges in an area.

An important practical control of interchange spacing from an operational standpoint is the balance between freeway and city street service. All vehicle trips which take place in an urban area result from the travel desires between land uses and the basic function of the freeway is to provide for most of the movement portion of the trip. The city street permits fulfillment of the trip purpose by providing terminal distribution of traffic and direct access to the land. The city streets also serve the short trips. If the interchanges on the freeway are spaced too closely, many of the short trips will be attracted to the freeway and the resultant congestion may impair the freeway's function of movement. If the interchanges on a freeway are too far apart, too many intermediate length trips will remain on the city street system, causing congestion and delay on this system. The proper balance between freeways and city streets permits each system to supplement the other and operate at optimum efficiency.

Internal Factors

The internal factors which influence the spacing of interchanges are geometric features and operational characteristics. Operational characteristics of a freeway are governed largely by its geometric features.

The geometric and operational features which must be considered in determining the proper spacing for interchanges are proper marking and directional signing, maneuver areas and weaving sections, and accident experience.

The modern freeway, when carrying a full load of vehicular traffic, requires a signing system which provides easily understood directions for the traveler. These directions should be given well in advance so that the individual motorist will have sufficient time to move from one lane to another with as little friction as possible. There must be sufficient distance between interchanges for the motorist to read, comprehend, and act upon the messages on the signs. If sufficient distance is not allowed, the motorist will become confused and act erratically and the free flowing characteristics of the freeway will be destroyed.

Weaving is the operational feature which may give the most trouble in conjunction with interchanges. For this reason sufficient spacing must be maintained between interchanges to accommodate the weaving which will occur. The absolute minimum spacing between interchanges with light to intermediate weaving volumes should be 1800 feet. The normal minimum spacing is approximately 2600 feet and the preferable

minimum spacing should be 4200 feet (7). In areas of concentrated urban development where demands for ingress and egress to the freeway are so high that if they are accommodated, the free flowing characteristics of the freeway would be destroyed, the designer may have to use a system of criss-cross or nested arrangement of ramps. This makes possible a greater number of ramps by using overlap, while still maintaining minimum spacing.

An important factor to consider in determining the proper spacing of interchanges is the effect of the interchange location on traffic accidents. The major locations of accidents on modern high-speed freeways are the interchanges where cars merge with or diverge from the through traffic stream (8). Consequently, for every interchange that is built, there will be increased opportunity for accidents.

In selecting the proper spacing for interchanges, a factor which must always be considered is the benefit-cost ratio. On the Interstate Defense System of Highways, any interchange spacing of less than two miles in an urban area must be justified by the benefit-cost study (9). This is a requirement of the Bureau of Public Roads and is best stated in the instructions for completing the estimate of cost for the Interstate system in accordance with Section 104(b)5, Title 23, U. S. Code, Highways. The instructions state in part:

> It is important that interchanges be located so as to properly discharge and receive traffic from other Interstate and and Federal-aid system routes, or major arterial highways or streets. It is equally important that they not be spaced so closely as either to unnecessarily increase the cost of the system or interfere with the freeflow and safety of traffic on the Interstate System.

> Interchanges within urban areas should not be spaced closer than an average of two miles, in the suburban sections of urban areas not closer than four miles, and in rural sections average not closer than eight miles
>
> Obviously, however, in consideration of the varying nature of the highway street or road systems with which the Interstate System must connect the spacings between individual adjacent interchanges must vary considerably. In urban areas the minimum distance between interchanges should not be less than one mile and in rural areas not less than three miles. Under normal circumstances the increased cost of construction resulting from the development of an interchange should have a net benefit-cost ratio of not less than 1.0.

A large number of interchanges could probably be justified by this method but it may not be desirable to build them because of other factors already discussed.

Perhaps the best measure of the efficiency of ramp spacing on a freeway is the total overall travel time of the vehicles in the system of streets and freeway. The total travel time in the system is the total amount of time that it takes for all the vehicles to travel through the system during a specified period of time. Using total travel time as a criteria for spacing, it would be desirable to space the interchanges in such a manner as to optimize the total travel of all vehicles traveling on the freeway and streets in the system. This goal may possibly result in penalizing some of the motorists while benefiting others in making some trips. While optimization of total travel time is important in the selection of ramp spacing, other factors which have already been discussed which influence ramp spacing should also be given serious consideration.

CHAPTER II

COLLECTION OF DATA

Study Site

The area in the vicinity of the North Freeway comprises an area lying north of the Central Business District of Atlanta as shown in Figure 1. Figure 2 shows this area in relation to the Interstate System of Defense Highways in the Atlanta area.

The land use in this area consists mainly of small businesses, apartment houses, boarding houses, insurance offices, medium and small size hotels, service stations and old residences. The majority of the traffic in this area during peak hours is traffic which is passing through the area rather than having a destination within the area.

The street system within this area consists of three arterials running in an east-west direction and five arterials running generally in a north-south direction. The North Freeway runs north and south approximately in the center of the area. A frontage road, Williams Street, is located on the east side of the North Freeway. Williams Street is an access street serving adjoining businesses and residences. This street has one-way operation north, north of Tenth Street and two-way operation south of Tenth Street. The northbound on-ramps to the North Freeway enter from Williams Street at Tenth and Fourteenth Streets. On the south portion of the North Freeway, there is a left-hand on-ramp entering the freeway from Williams Street. This entrance

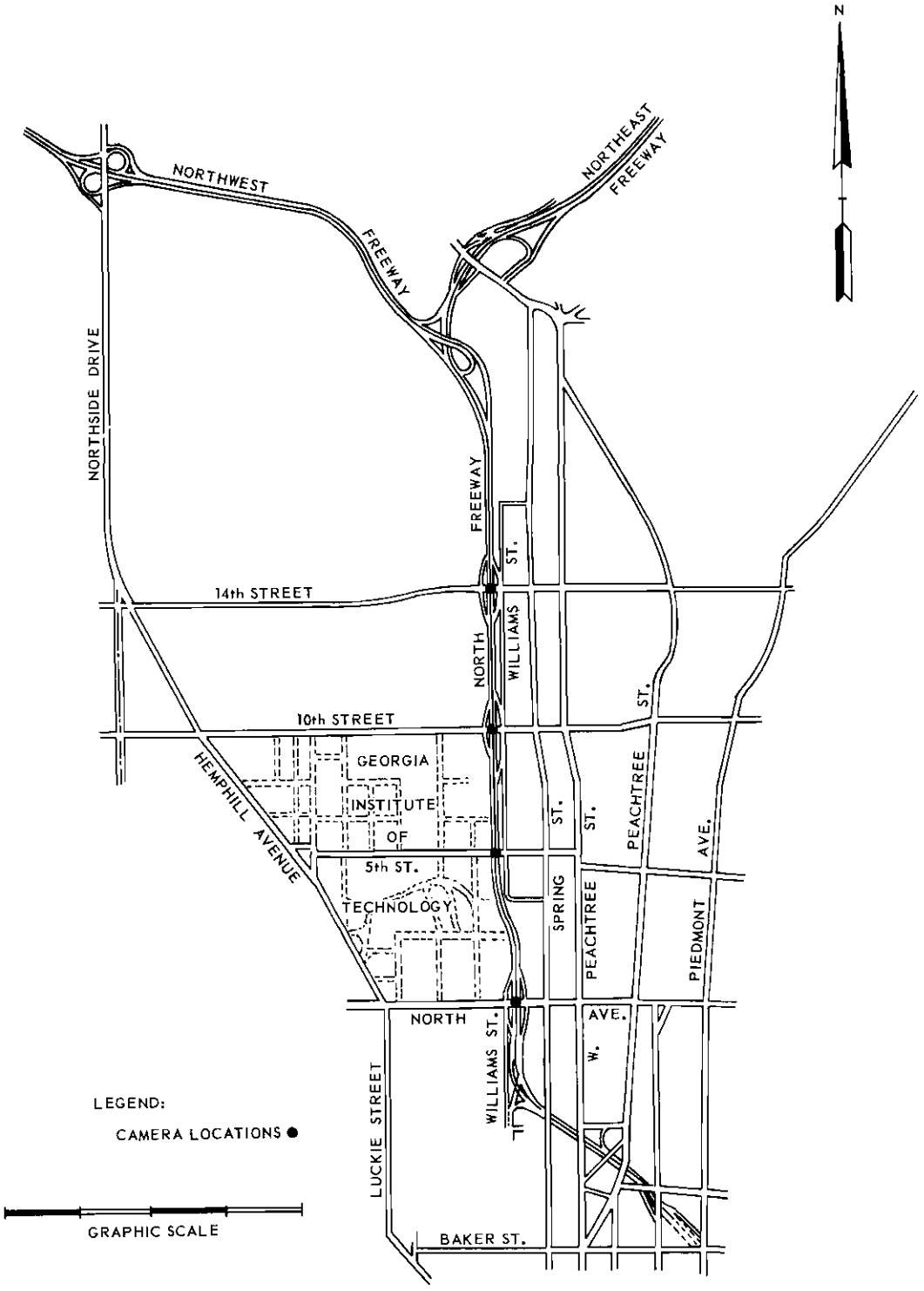

Figure 1. Street System in the Vicinity of North Freeway.

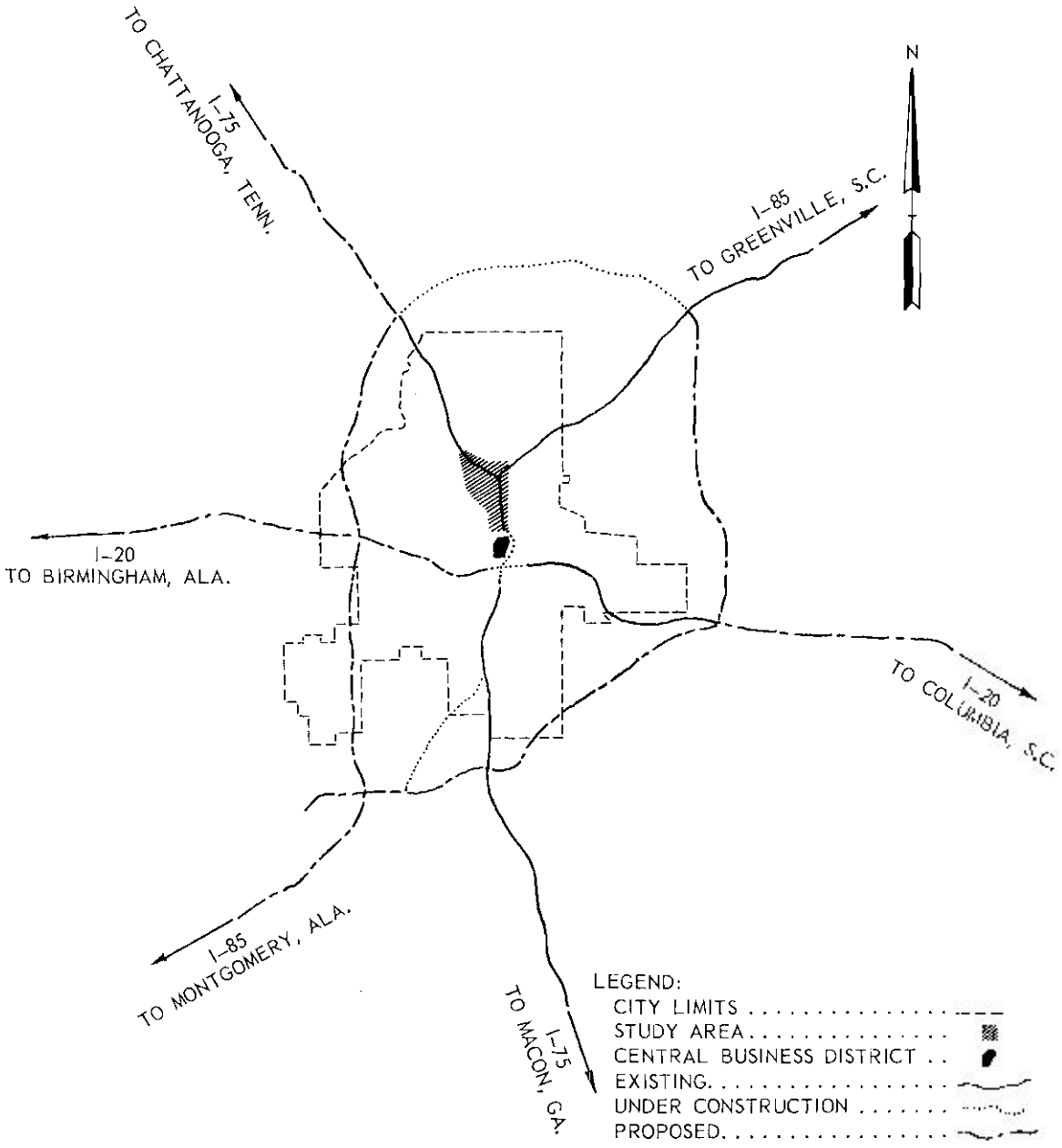

Figure 2. Atlanta Freeway System.

is 0.089 miles south of the North Avenue interchange. The junction of the Northeast and Northwest Freeways is 0.30 miles north of the Fourteenth Street interchange.

Within the area shown in Figure 1 the North Freeway consists of three 12-foot lanes in the northbound and southbound directions. The Northeast and Northwest Freeways both consist of two 12-foot lanes. The freeways and ramps are constructed of concrete and to provide color contrast, the concrete on the ramps has been darkened.

The interchanges on the North Freeway at North Avenue, Tenth Street, and Fourteenth Street are diamond type interchanges with the on-ramps entering directly onto the freeway with no acceleration lanes provided. The design speed used on the freeway was 50 miles per hour and the design speed used on the ramps was 35 miles per hour. The design hour volume used was 1500 vehicles per lane per hour. The maximum vertical grade used in the design was five per cent and the maximum horizontal curvature used was a three degree curve. The interchange at Fifth Street is a grade separation only with no entrance to the freeway provided. The freeway from North Avenue to Peachtree Street was completed and opened to traffic in the spring of 1950.

Study Procedure

As set forth in the introduction the purpose of this study was to determine the influence of ramp spacing on the traffic flow characteristics of the Atlanta Freeway System. To fulfill the purpose of this study, it was necessary to vary the spacing between ramps and to

study traffic flow characteristics under these variable conditions and compare them to traffic flow characteristics obtained when the freeway was operating with normal ramp spacing.

The only method for varying the spacing between ramps, without making permanent or semi-permanent changes in the freeway, was to close certain ramps during the peak period of traffic flow. When a ramp was closed, the interchange was effectively eliminated and the ramp spacings of the "remaining interchanges" were changed.

In carrying out the study, the northbound on-ramps located at North Avenue, Tenth Street, and Fourteenth Street were closed during the afternoon peak period of traffic flow between 4:30 P. M. and 6:30 P. M. for a period of two weeks. Each on-ramp was closed separately and only one ramp was closed at any one time. Table 1 shows the distance between interchanges for each ramp closure. The distances vary from a maximum of 1.458 miles to a minimum of 0.089 miles. The first week that each ramp was closed, the traffic was allowed to stabilize to permit motorists to establish new travel patterns. Most of the necessary studies were made during the second week of each ramp closure.

Figures 3 and 4 show the method used for closing the ramps. The ramps were closed while still maintaining traffic on the parallel frontage road, Williams Street, when the northbound on-ramps at Tenth and Fourteenth Streets were closed. The barricades were placed at the nose of the ramps as seen in Figure 4 to inform the motorists using the freeway that the ramp was closed. When the motorists on the freeway approached the ramp entrance, he could easily see that the ramp entrance

Table 1. Distance Between Interchanges for Various Ramp Closings in Miles

	Normal Operation (No Ramps Closed)	North Avenue Northbound On-Ramp Closed	Tenth Street Northbound On-Ramp Closed	Fourteenth Street Northbound On-Ramp Closed
Williams Street*	0.089	0.897	0.089	0.089
North Avenue	0.708		1.067	0.708
Tenth Street	0.359	0.359		1.250
Fourteenth Street	0.891	0.891	0.891	
Peachtree Road	1.458	1.458	1.458	1.458
Piedmont Road				

*Left-Hand On-Ramp

Figure 3. Method of Closing Tenth Street Northbound On-ramp Viewed from Williams Street.

Figure 4. Method of Closing Tenth Street Northbound On-ramp Viewed from North Freeway.

is closed and will not slow down or change lanes as he might do with the ramp entrance open.

Studies were made at four different locations on the freeway under normal operation of the freeway (i.e., all ramps open), with North Avenue northbound on-ramp closed, with the Tenth Street northbound on-ramp closed, and with the Fourteenth Street northbound on-ramp closed. The four locations were North Avenue, Fifth Street, Tenth Street, and Fourteenth Street. The data collected at these respective locations were the volume, speed, and density in each lane on the freeway and the ramp volume. These data were collected between 4:30 P. M. and 5:10 P. M., and between 5:20 P. M. and 6:00 P. M. by the use of time-lapse photography. The cameras used in making the movies would only hold enough film for forty minutes of continuous filming. Unloading and reloading the cameras necessitated the ten minute gap in the data collection. All data collected during these two periods were summarized in five minute time increments.

Speed and Delay Runs

An effective measure of the level of service which exists on any highway is the overall travel time between two points on the highway (10). Using this principle, the overall travel time on the freeway was measured by making speed and delay runs. The data which were obtained on each run were: overall travel time, total running time (time that vehicle was actually moving), total delay time and cause of each delay, overall travel speed, and running speed. Travel time information was obtained for each two-tenth of a mile increment and then compiled

between each interchange and for the entire freeway length under study. Using the data obtained with the speed and delay studies and the total hourly volume counts, it was possible to obtain the total vehicle-minutes of travel time for all vehicles using the freeway during each condition of ramp closure. Using the length between each interchange and the total hourly volume counts, it was also possible to obtain the total vehicle-miles of travel for all vehicles using the freeway under the conditions discussed above.

Equipment and Instrumentation

Time-lapse photography was used to collect the data at the four study locations on the North Freeway. The cameras used for the time-lapse photography were Bolex 16 mm. movie cameras driven by Bodine 110 volt AC synchronous motors as shown in Figure 5. The cameras were geared to the motor to produce movies at a rate of 100 frames per minute. These particular cameras had a film capacity of 100 feet, and therefore, could be used to collect data for a forty minute period only. The time interval between each frame was six-tenths of one second. Because an accurate time interval was very important, a synchronous motor was used to drive the camera. The shutter speed used was one-fifteenth of a second and this shutter speed was sufficient to prevent blurring of the moving vehicles at the relatively slow speed (about 5 to 30 miles per hour) which occurred during the peak hour. When this shutter speed was used to photograph vehicles at higher rates of speed, some blurring of the vehicles occurred.

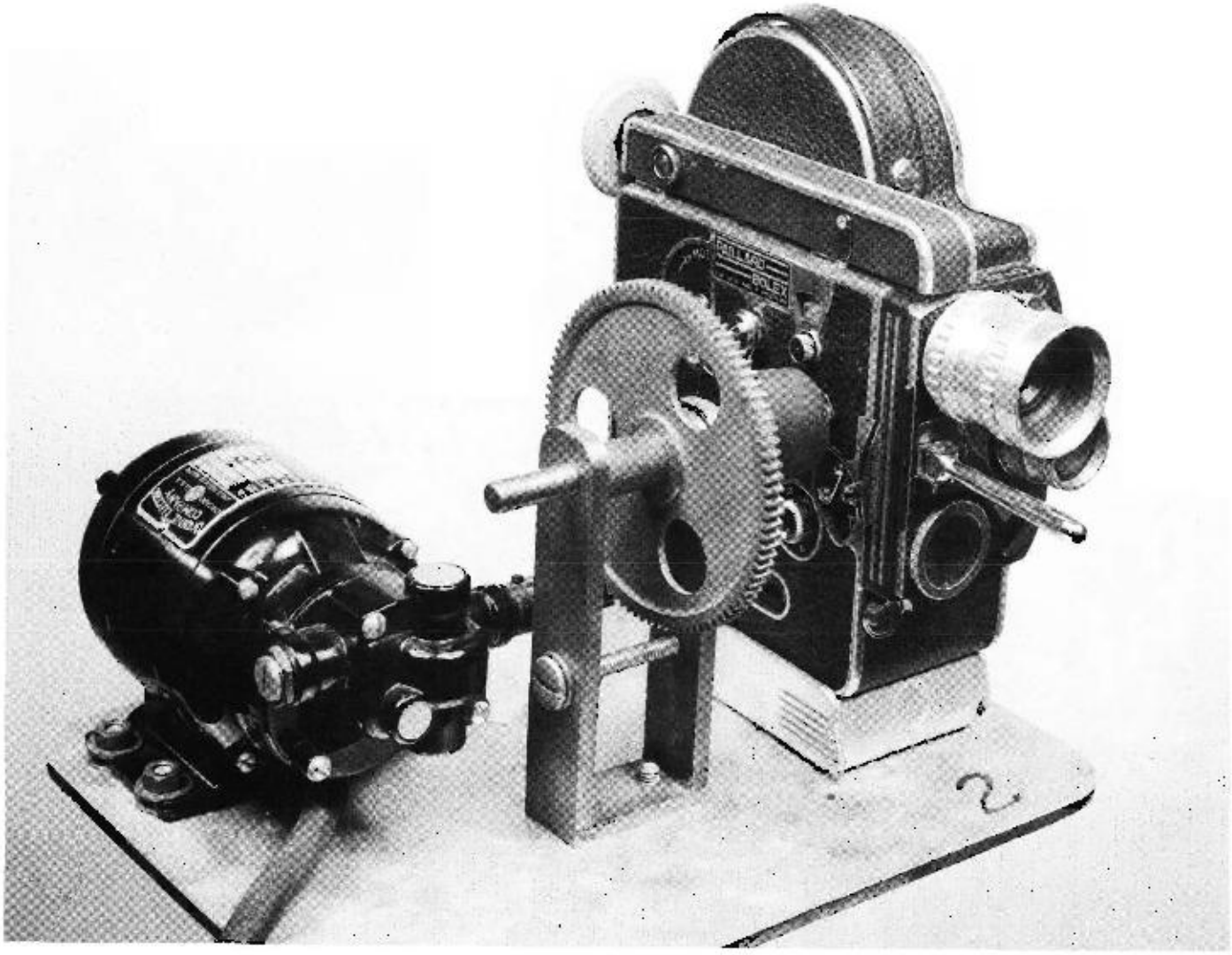

Figure 5. Time-lapse Movie Camera Equipment.

On the drive shaft from the motor to the camera, a safety device was installed to prevent the camera from extensive damage in the event the film jammed. The drive shaft was made in two parts, and a rubber clutch was used to connect the shaft. If the camera jammed for some reason, this clutch would twist off rather than damaging the camera.

Because identification of vehicles was necessary in the analysis of data, color film was used whenever possible. However, because some of the photography was made under poor light conditions, the use of high-speed black and white film was necessary in some instances.

Before any photography could be taken, a grid system was painted on the pavement at each study location. The grid was painted at 50 foot intervals and perpendicular to the centerline of the freeway at all study locations. Figure 6 is a sketch of a typical grid system layout that was used for a study of freeway and on-ramp traffic characteristics. Figure 7 shows a typical field set up of the camera with the grid system on the pavement in the background.

Analysis of Film

The film made at each of the study locations was analyzed by projecting it through a time and motion study projector. Using this projector the film was studied one frame at a time by advancing it through the projector using a solenoid switch.

To analyze the film, the picture was projected onto a screen with a grid reproduced on the screen to match the grid on the pavement. In this manner the vehicle speeds could be obtained by measuring the

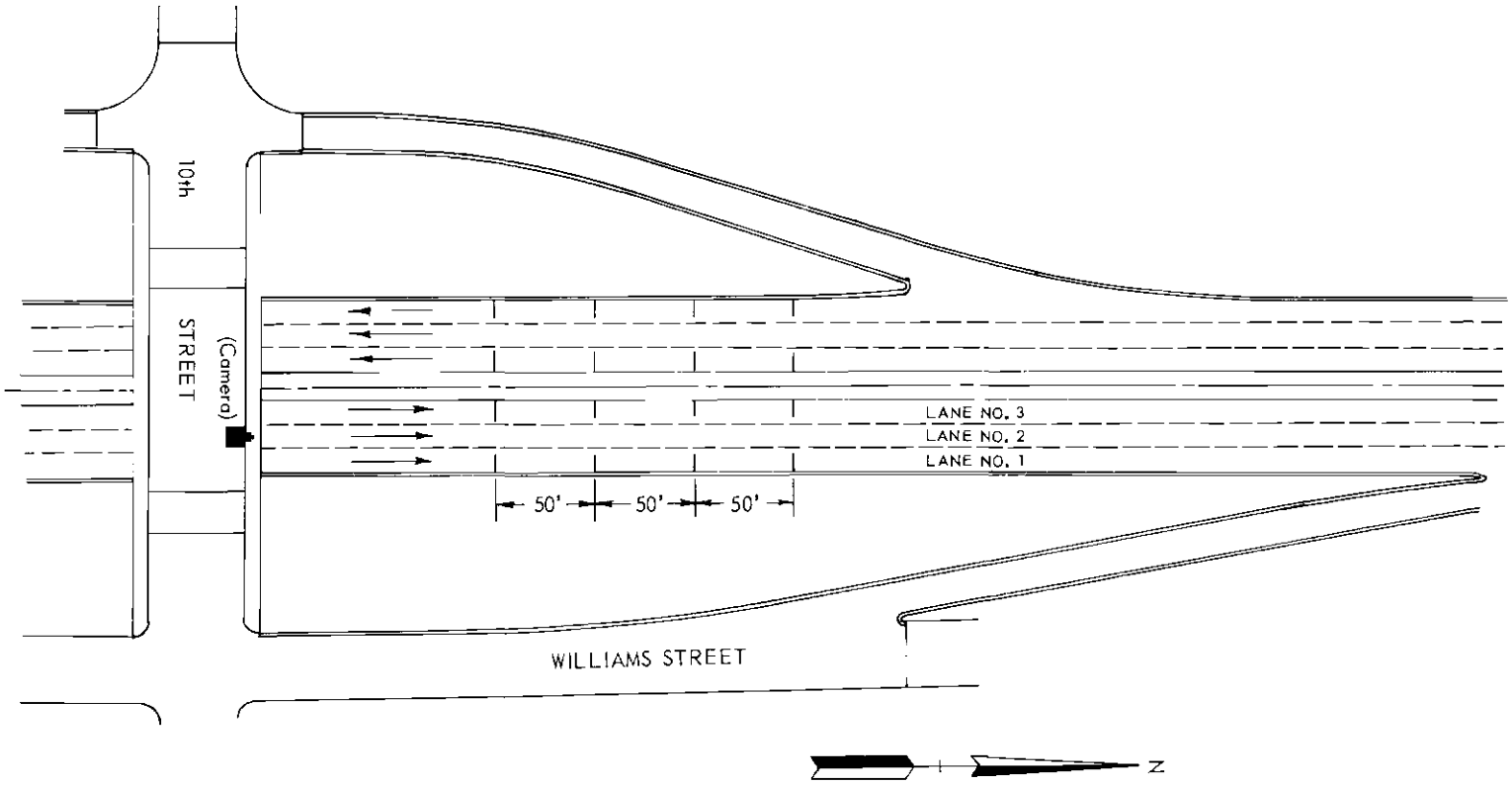

Figure 6. Layout of Typical Grid System.

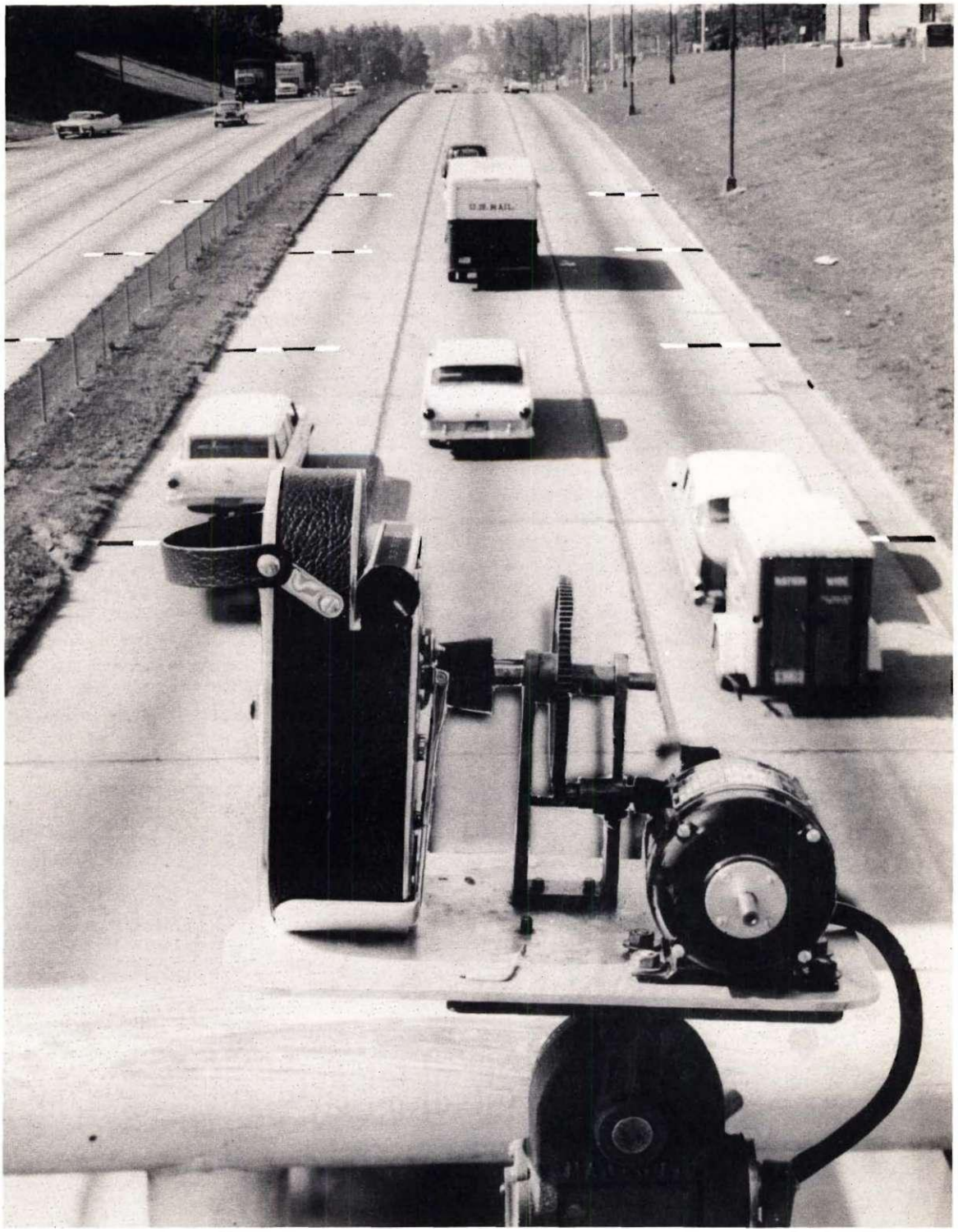

Figure 7. Field Location of Time-lapse Movie Camera at Tenth Street (Looking North).

distance of movement of a vehicle for a specified number of frames of movie film and dividing the distance by the time required for the vehicle to move between the frames of film measured.

The following information was collected for each location studied:

1. Vehicle volume
2. Vehicle speeds
3. Classification of vehicles into passenger car, single unit truck, semi-trailer truck and bus.

This information was collected in five minute increments of time. By using the frame counter which is on the projector, each five minute increment could be determined by counting off each 500 frame interval. These data were collected for each lane on the freeway. Also the volume and classification of vehicles were obtained for the ramp. It was not possible to obtain the speed of the vehicles on the ramps.

A systematic sample of 20 vehicles were sampled for each five minute period to determine average speeds for each lane for this time period. Statistical analysis indicated that a sample of this size was sufficient to give the true average speed within two miles per hour ninety-five per cent of the time (11).

A more detailed discussion of the methods used to make analyses of time-lapse photography can be found in the March, 1960, issue of Traffic Engineering (12).

CHAPTER III

ANALYSIS OF DATA

Computation of Results

In order to analyze the data, it was necessary to take the raw data from the film analysis, such as vehicle volume and vehicle speeds and refine these data to a usable form.

The three basic factors or elements of traffic flow are: (1) Volume [V] which is defined as the number of vehicles passing a point per unit of time; (2) Speed [S] expressed in miles per hour, and (3) Density [D] defined as the number of vehicles per mile of roadway or lane. The first two of these three factors were obtained from the analysis of the film. The third factor, density, was obtained from the other two factors, speed and volume. The density for each five minute interval was computed by dividing the five minute volume by the average speed for that interval. This gives the density for that particular location for each five minute time interval.

The three basic factors--volume, speed, and density--that were studied were computed for a location just after the ramp entrance. The speed was obtained from the film analysis before the ramp entrance and was assumed to be the same both before and after the ramp entrance. It was assumed that the vehicles entering the freeway from the ramp during each five minute time interval entered lane number one, the shoulder lane. The middle lane was designated as "lane number two" and the median

lane was designated as "lane number three." The density in lane number one was computed by adding the number of vehicles entering the freeway from the ramp to the volume of vehicles on the freeway before the ramp entrance and dividing this total by the average speed. The total volume on the freeway was computed by simply adding the volumes in the three lanes for each time interval. The average lane volume, speed and density were computed by adding each of these factors over the three lanes and dividing by three. This was done for each of the five minute time intervals.

In summary, the following information was evaluated from the time-lapse movies:

(1) Lane volumes

(2) Lane speeds

(3) Lane density

(4) Total volume

(5) Average lane volume

(6) Average lane speed

(7) Average lane density

The above data were computed for each five minute time interval for each of the four selected study locations. Ten five minute time intervals between 5:00 P. M. and 6:00 P. M. were used in this study. The times used were from 5:00 P. M. to 5:10 P. M. and from 5:20 P. M. to 6:00 P. M. These data were collected at each of the four study locations for two days during each of the ramp closures and for normal operation of the freeway.

To determine the total overall travel time and the total overall travel distance of all the vehicles on the North Freeway, the freeway was divided into a system of links. Each of these links consisted of that portion of the North Freeway between interchanges. The links as they were designated are shown in Figure 8. The total overall travel time and the total overall travel distance on each of these links were computed. Using the vehicle volumes and travel times the total number of vehicle-minutes was computed for each link. Using the vehicle volumes and distances of each link, the total number of vehicle-miles was computed for each link. Totaling these figures the total overall travel time and travel distances were obtained for the North Freeway for all the vehicles using the North Freeway between 5:00 P. M. and 6:00 P. M. Table 2 shows the total overall travel time on the North Freeway and Table 3 shows the total overall travel distance.

Analysis of Variance

Analysis of variance is probably the most powerful procedure in the field of experimental statistics. It allows data collected to be rigorously analyzed and the conclusions to be accompanied by probability statements as to the correctness of inferences. To carry out the analysis, it is necessary to formulate a mathematical model in terms of the unknown parameters and the associated random variables. The quantitative physical characteristics (dependent variables) of interest in this study are the following:

(1) Volume

(2) Speed

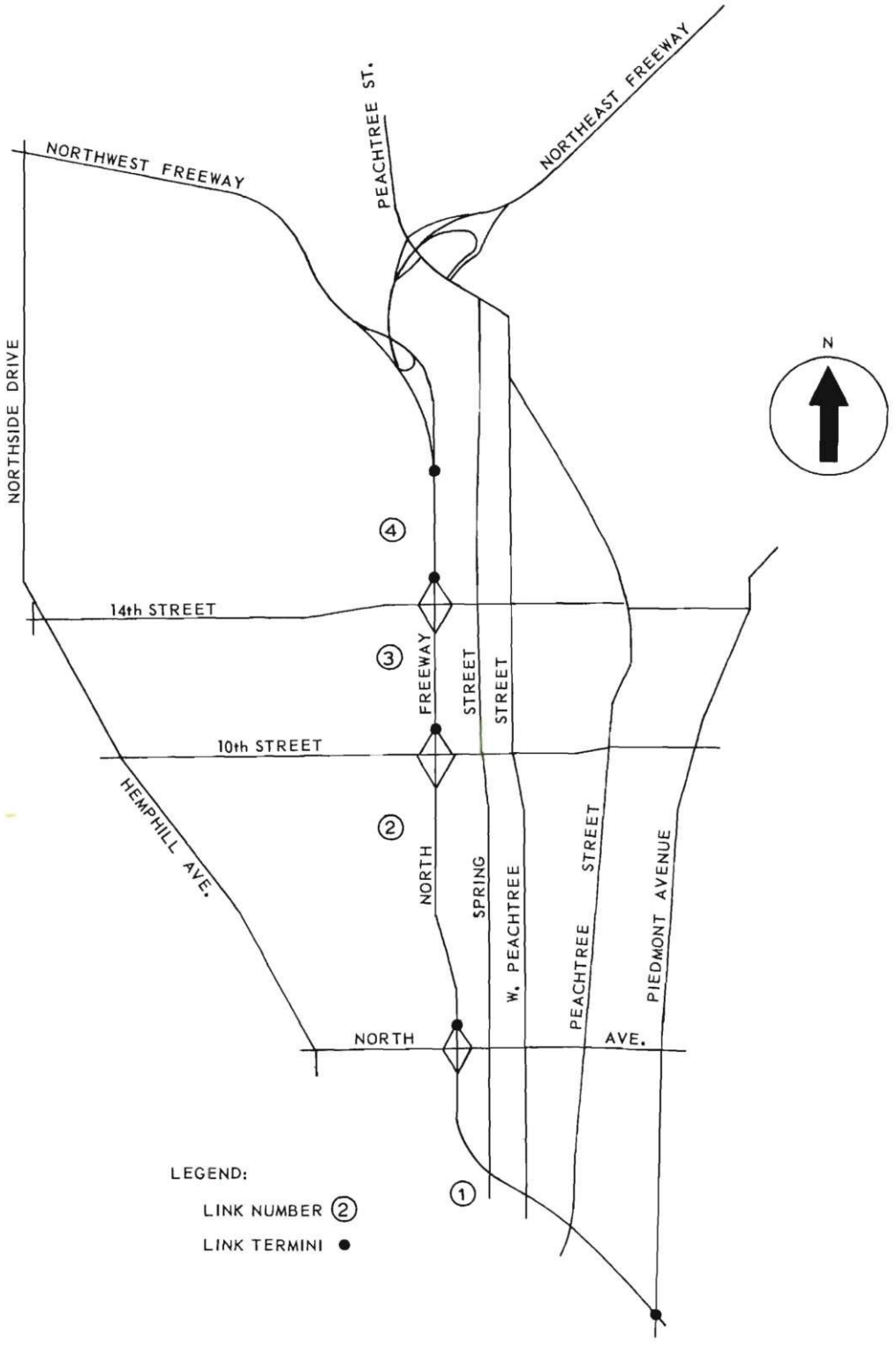

Figure 8. Network Links on North Freeway.

Table 2. Total Overall Travel Time on the North Freeway in Vehicle-Minutes (5:00-6:00 P. M.)

Link Number	Day	Total Travel Time (Vehicle-Minutes)			
		Normal Operation (All Ramps Open)	North Avenue Northbound On-Ramp Closed	Tenth Street Northbound On-Ramp Closed	Fourteenth Street Northbound On-Ramp Closed
1	1	2413	2915	2228	1833
	2	2281	2538	2462	1920
	3	2518	2696	2228	1893
2	1	5185	3764	3760	3235
	2	5325	3843	4524	3253
	3	5239	3815	6074	3245
3	1	3292	1991	1592	1751
	2	3386	2203	2970	1877
	3	3339	2117	2289	1833
4	1	2425	3007	1872	1716
	2	5320	2936	1609	2010
	3	2882	4137	6876	3234
Total	1	13315	11677	9452	8535
	2	17312	11520	11565	9060
	3	13978	12765	17467	10205

Table 3. Total Overall Travel Distance on the North Freeway in Vehicle-Miles (5:00-6:00 P. M.)

Link Number	Day	Total Travel Distance (Vehicle-Miles)			
		Normal Operation (All Ramps Open)	North Avenue Northbound On-Ramp Closed	Tenth Street Northbound On-Ramp Closed	Fourteenth Street Northbound On-Ramp Closed
1	1	1372	1605	1355	1155
	2	1492	1577	1340	1064
	3	1432	1596	1385	1113
2	1	2555	2509	2564	2268
	2	2723	2465	2549	2190
	3	2639	2494	2604	2229
3	1	1219	1219	1337	1167
	2	1224	1224	1144	1173
	3	1222	1222	1116	1170
4	1	1455	1455	1206	1355
	2	1165	1398	1305	1340
	3	1310	1427	1296	1347
Total	1	6601	6788	6462	5945
	2	6604	6664	6338	5767
	3	6603	6739	6401	5859

(3) Density

(4) Total travel time (expressed in vehicle-minutes)

(5) Total travel distance (expressed in vehicle-miles)

(6) Overall running speed

(7) Overall travel speed

The independent variables of interest are as follows:

(1) Ramp condition [R] (Ramp opened or closed)

(2) Position [P] (Position of ramp on freeway)

(3) Lane number [L]

(4) Day [D]

(5) Replication [T] (Replication, in this case, would be each five minute time interval)

To carry out an analysis of variance on each of the dependent variables in this study, formulation of two different mathematical models was necessary.

The mathematical model necessary for an analysis of the volume, speed, and density which occurred on the freeway is as follows:

$$Y_{ijklm} = \mu + R_i + P_j + L_k + D_l + RP_{ij} + RL_{ik} + RD_{il} + PL_{jk}$$

$$+ PD_{jl} + LD_{kl} + RPL_{ijl} + RPD_{ijl} + RLD_{ikl} + PLD_{jkl}$$

$$+ RPLD_{ijkl} + T_m(R_i P_j L_k D_l)$$

The primary variables used with this model are shown in Table 4. In effect this model states that an individual observation of volume, speed, or density on the freeway located at the j^{th} position, in the k^{th} lane, on the l^{th} day, under the i^{th} ramp condition, in the m^{th} replication, will be an expected value μ plus the sum of any main effects and interaction effects due to the independent variables.

The mathematical model necessary for an analysis of the speed and delay studies, total overall travel time, and total overall travel distance on the freeway is as follows:

$$Y_{il} = \mu + R_i + D_l + RD_{il}$$

The primary variables used with this model are shown in Table 5.

In order to reach conclusions about the significance of the independent variables of interest in these models, it is necessary to accompany conclusions with probability statements as to the correctness of the conclusion. To do this a "level of significance" is established. The level of significance refers to the probability that the existence of real differences among the levels of an independent variable is concluded when only differences caused by chance fluctuations in the data exist. When the ten per cent level of significance is used, this means that the probability of concluding that there are real differences in the levels of the independent variables, when in fact there are no differences, is 0.10.

Table 4. Primary Variables for Analysis of Variance of the Volume, Speed, and Density on the North Freeway

Factor	Abbreviation	Subscript	No. Levels	Model
Ramp Condition	R	i	4	Fixed
Position	P	j	4	Fixed
Lane	L	k	3	Fixed
Day	D	l	2	Random
Replication	T	m	10	Random

Table 5. Primary Variables for Analysis of Variance of the Total Overall Travel Time, Total Overall Travel Distance, and Speed-Delay Studies on the North Freeway

Factor	Abbreviation	Subscript	No. Levels	Model
Ramp Condition	R	i	4	Fixed
Day	D	l	3	Random

CHAPTER IV

DISCUSSION OF RESULTS

In the analysis of variance of the volume, speed, and density on the North Freeway, 960 separate bits of data were analyzed. These data were the volume, speed, and density on the freeway for each five minute time interval from 5:00 P. M. to 5:10 P. M. and from 5:20 P. M. to 6:00 P. M. for each lane, day, ramp condition, and study location. Ramp condition refers to what condition existed on the freeway at the time the data were collected. The four ramp conditions are: normal operation, North Avenue northbound on-ramp closed, Tenth Street northbound on-ramp closed, and Fourteenth Street northbound on-ramp closed. The data were collected for each of the ten five minute time intervals for three lanes at each of the four study locations for two days for each of the four different ramp conditions. The mathematical models used in analyzing these data were presented in Chapter III. The results of the analysis of variance of these data are shown in Tables 9, 10, and 11.

Analysis of Variance of Data

In performing an analysis of variance with such a relatively large number of interaction terms, one must be extremely careful in analyzing the data to avoid reaching the wrong conclusions about significance of the variables. To illustrate what is meant the reader is referred to Table 10, the analysis of variance of the speeds on the North Freeway.

Studying the ramp condition factor in this table would lead one to conclude that there is no significant difference in the speeds on the freeway under different ramp conditions. However, this is misleading since the ramp-day interaction term which is used to test the ramp condition factor is itself highly significant. This high significance indicates that the mean-square of the ramp-day interaction term is high in relation to the error term which is used to test the ramp-day interaction. The high value of the ramp-day interaction term results in a relatively low ratio of the ramp condition term to the ramp-day interaction term. This low ratio, together with the low number of degrees of freedom will indicate that there is no significant difference when actually there may be a significant difference. Tables 9, 10, and 11 were established using the conventional methods of analysis of variance and should be interpreted with care by the reader.

Two of the interaction terms on volume, speed, and density were selected from the tables for further analysis. These terms were the ramp-position interaction term and the ramp-position-lane interaction term. Figure 9 shows graphs which have been plotted of the ramp-position interaction term for volume, speed, and density for each of the four selected study locations. Figures 10, 11, 12, and 13 show graphs which have been plotted of the ramp-position-lane interaction terms for each of the four selected study locations under all ramp conditions. Tables 6, 7, and 8 contain the values which were used to plot Figures 9, 10, 11, 12, 13, and 14.

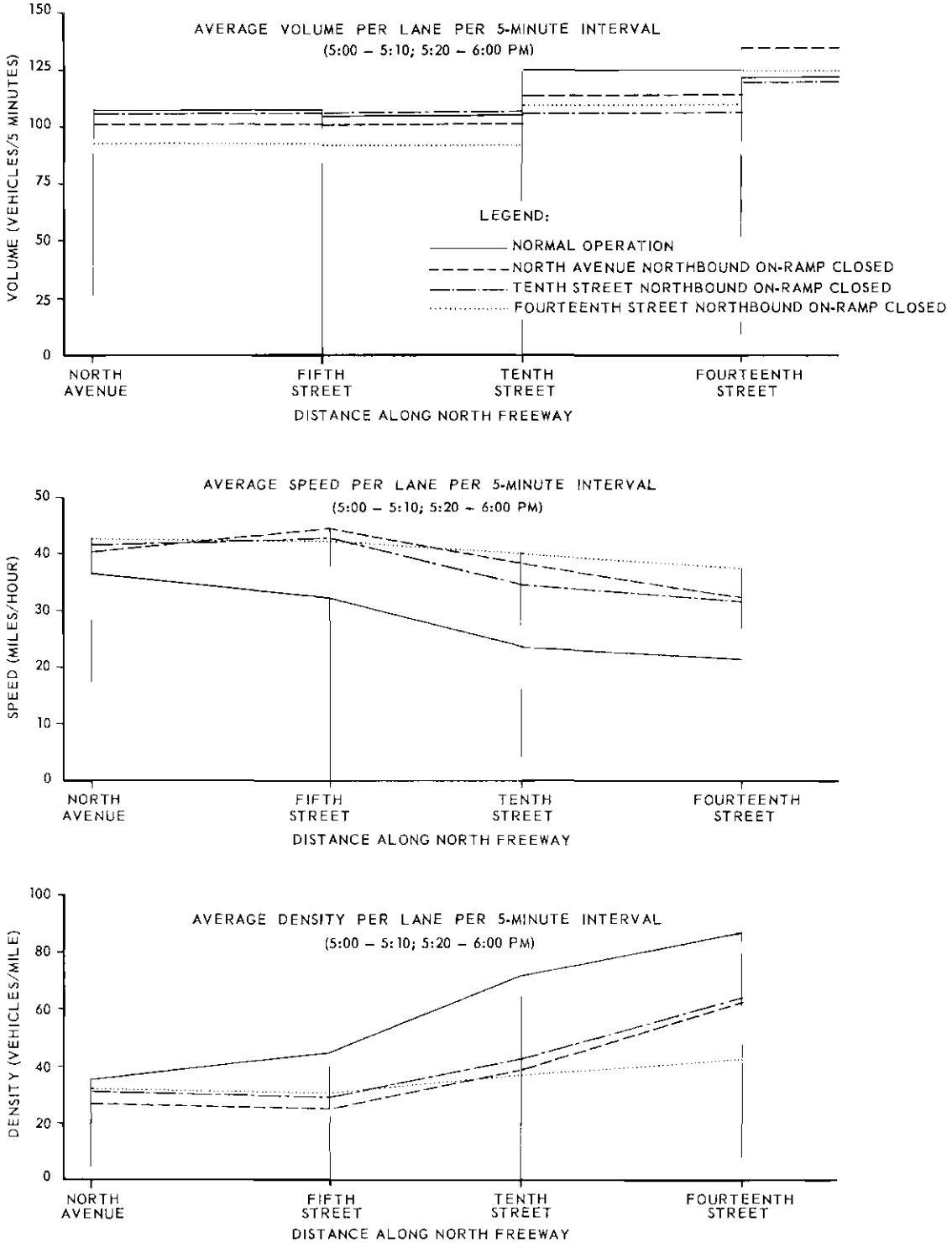

Figure 9. Average Volume, Speed, and Density Per Lane Per Five-Minute Time Interval on the North Freeway.

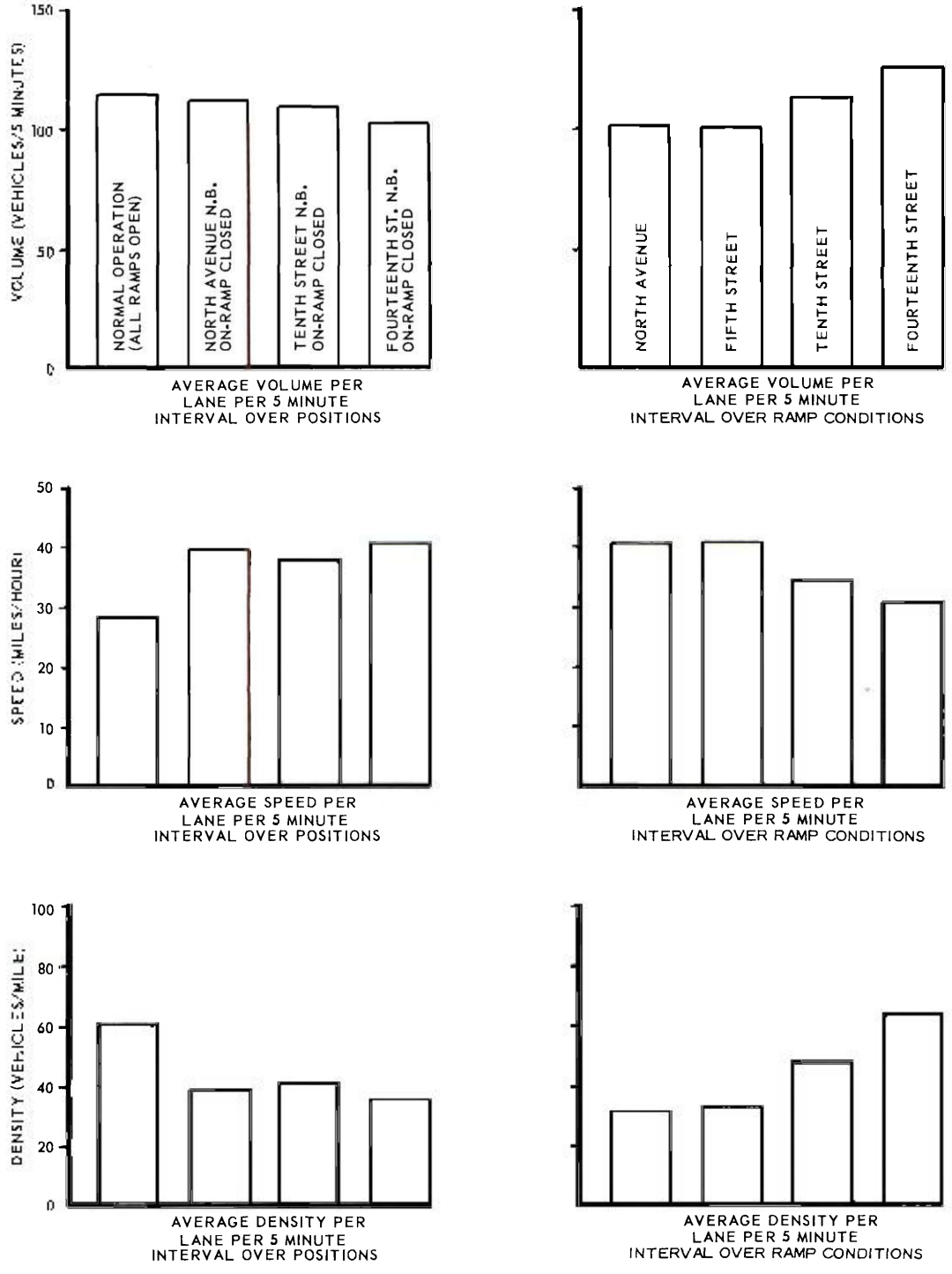

Figure 10. Average Volume, Speed, and Density Per Lane Per Five-Minute Time Interval on the North Freeway Over Positions and Ramp Conditions.

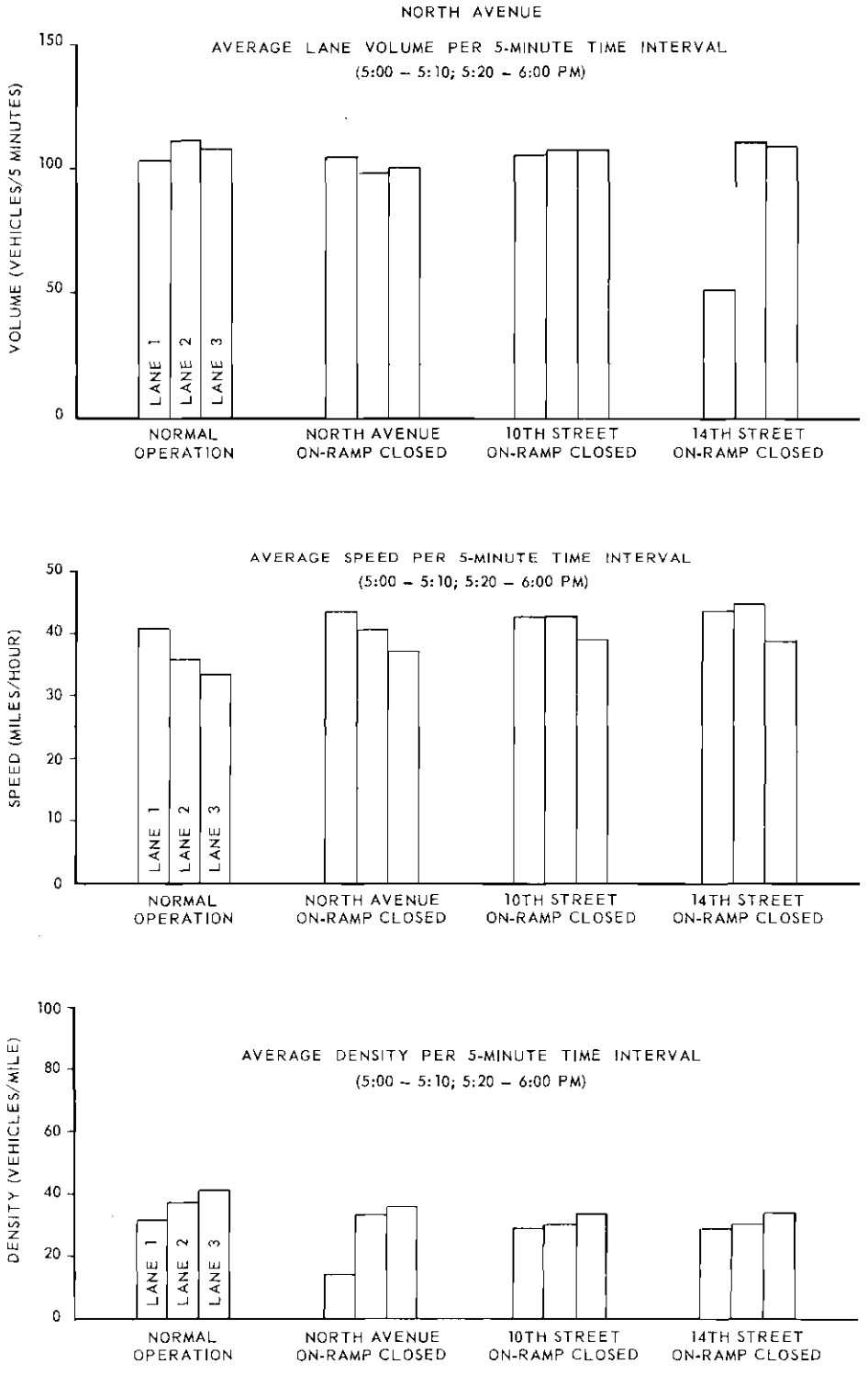

Figure 11. Average Lane Volume, Speed, and Density Per Five-Minute Time Interval on the North Freeway at North Avenue.

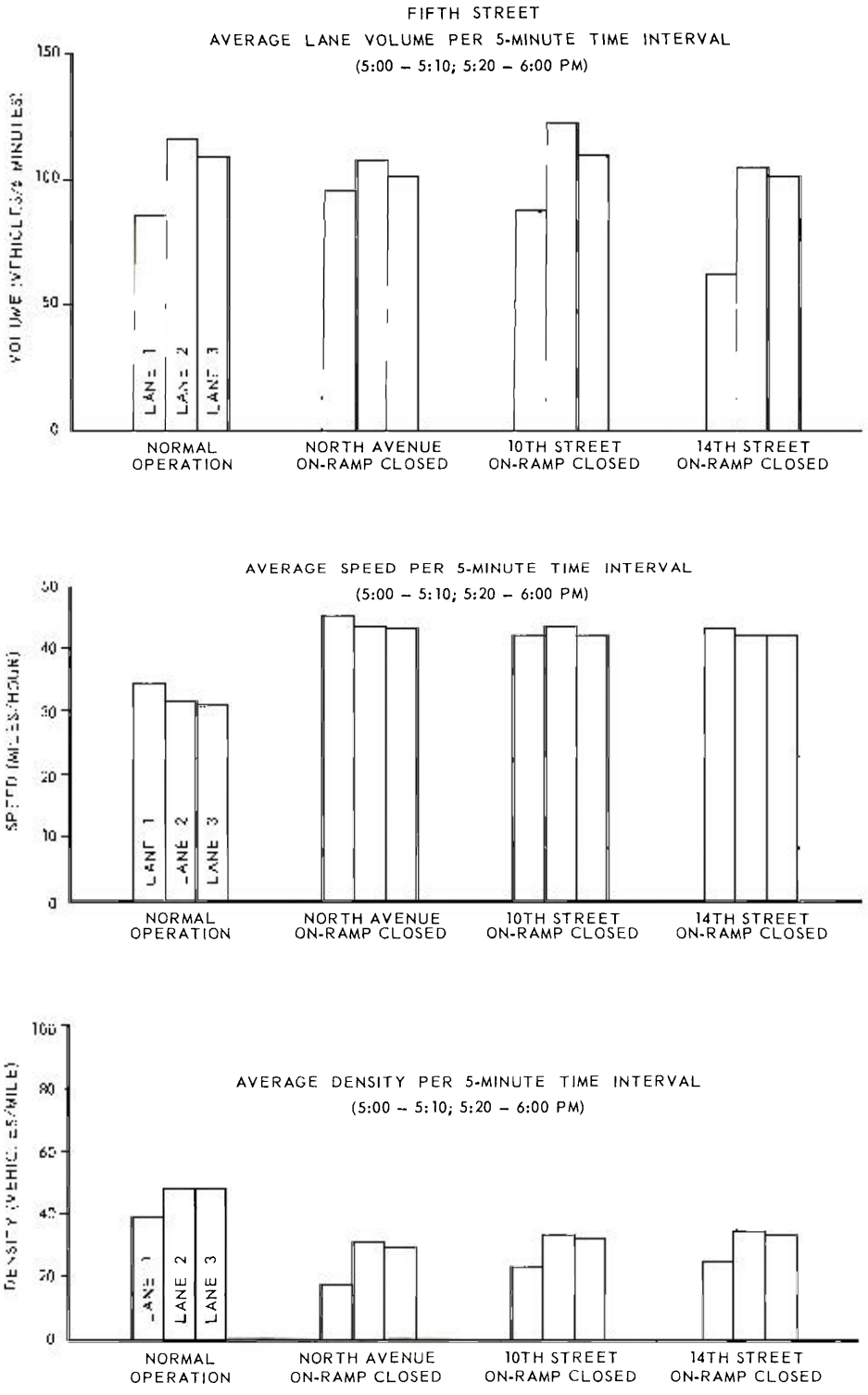

Figure 12. Average Lane Volume, Speed, and Density Per Five-Minute Time Interval on the North Freeway at Fifth Street.

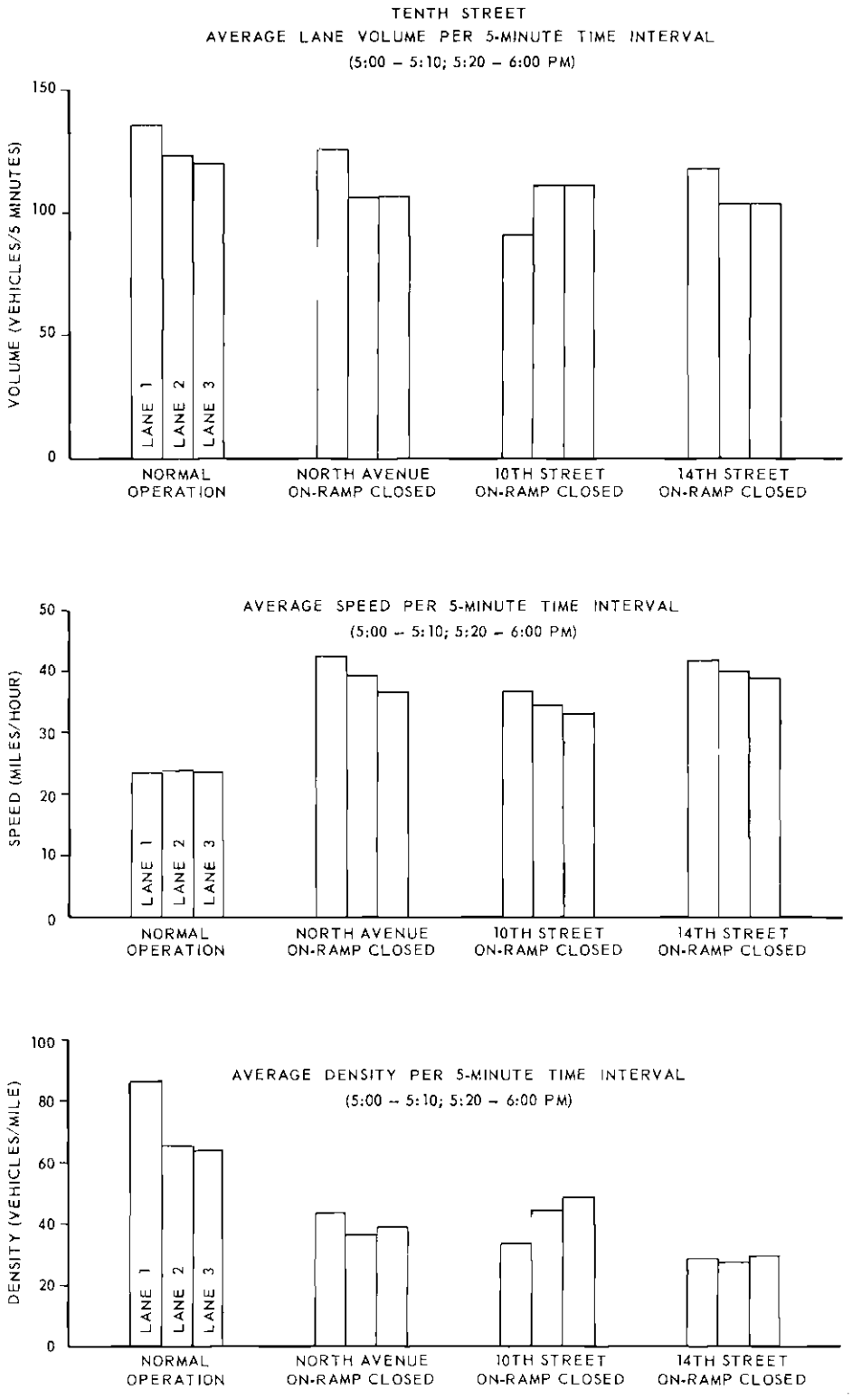

Figure 13. Average Lane Volume, Speed, and Density Per Five-Minute Time Interval on the North Freeway at Tenth Street.

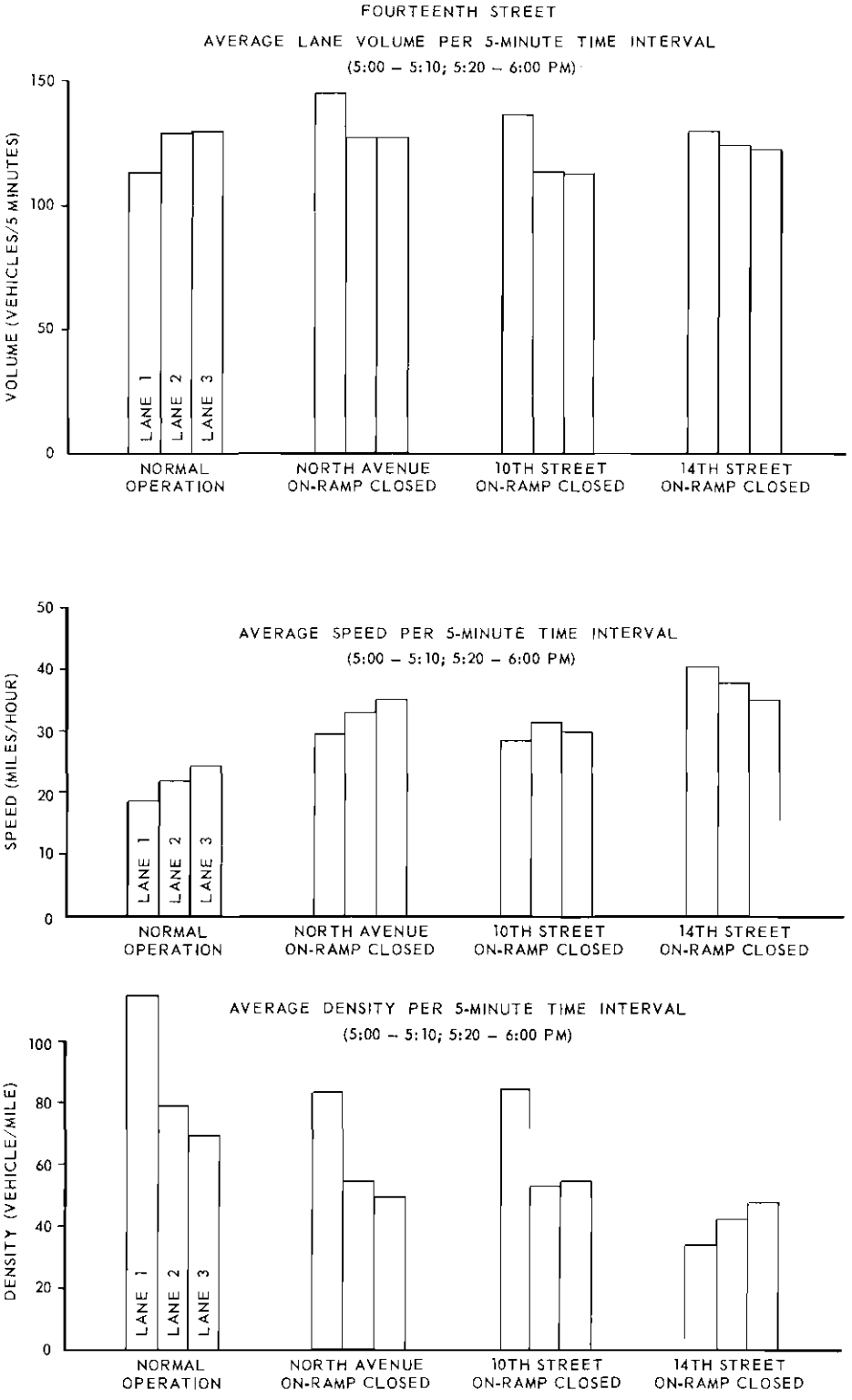

Figure 14. Average Lane Volume, Speed, and Density Per Five-Minute Time Interval on the North Freeway at Fourteenth Street.

Table 6. Average Lane Volume and Average Volume per Lane per Five Minute Time Interval on the North Freeway

Position	Lane	Normal Operation	North Avenue On-Ramp Closed	Tenth Street On-Ramp Closed	Fourteenth Street On-Ramp Closed
North Avenue	1	103.9	104.8	105.4	51.2
	2	111.5	99.4	107.6	111.5
	3	108.1	100.6	107.4	110.5
	Average Volume	107.8	101.6	106.8	91.1
Fifth Street	1	84.0	94.6	86.1	62.9
	2	116.0	108.5	122.4	106.2
	3	109.7	101.8	110.4	101.3
	Average Volume	103.2	101.6	106.3	90.1
Tenth Street	1	134.1	125.5	89.5	117.5
	2	122.0	106.8	111.6	103.7
	3	119.7	106.9	111.5	103.7
	Average Volume	125.3	113.1	104.2	108.4
Fourteenth Street	1	113.3	142.9	134.9	128.2
	2	127.6	127.0	114.4	124.3
	3	128.1	126.5	113.3	121.9
	Average Volume	123.0	132.1	120.9	124.8

Table 7. Average Land Speed and Average Speed per Lane per Five Minute Time Interval on the North Freeway

Position	Lane	Normal Operation	North Avenue On-Ramp Closed	Tenth Street On-Ramp Closed	Fourteenth Street On-Ramp Closed
North Avenue	1	41.0	43.6	42.9	43.8
	2	36.0	40.7	42.9	45.0
	3	33.3	37.3	39.0	39.0
	Average Speed	36.8	40.4	41.6	42.6
Fifth Street	1	34.6	45.4	42.3	43.1
	2	31.3	43.8	43.8	42.4
	3	30.9	43.3	42.2	42.4
	Average Speed	32.3	44.4	42.9	42.6
Tenth Street	1	23.5	40.3	36.9	41.8
	2	23.8	39.4	34.5	40.0
	3	23.7	36.7	33.0	38.9
	Average Speed	23.7	38.8	34.8	40.3
Fourteenth Street	1	18.8	29.6	28.9	40.4
	2	22.1	33.3	31.6	38.1
	3	24.3	35.2	30.0	35.2
	Average Speed	21.8	32.7	31.9	37.9

Table 8. Average Lane Density and Average Density per Lane per Five Minute Time Interval on the North Freeway

Position	Lane	Normal Operation	North Avenue On-Ramp Closed	Tenth Street On-Ramp Closed	Fourteenth Street On-Ramp Closed
North Avenue	1	31.7	14.2	29.5	28.5
	2	37.3	33.0	30.3	30.2
	3	40.9	35.8	33.3	34.0
	Average Density	36.6	27.7	31.0	30.9
Fifth Street	1	39.1	17.1	23.7	24.3
	2	48.9	30.6	33.7	35.2
	3	48.8	29.3	31.8	33.3
	Average Density	45.6	25.7	29.7	31.0
Tenth Street	1	86.2	43.1	33.5	38.9
	2	65.7	36.1	44.1	37.4
	3	63.2	38.9	48.4	39.4
	Average Density	71.7	39.4	42.0	38.5
Fourteenth Street	1	114.6	82.8	83.9	34.3
	2	78.6	54.7	52.7	42.0
	3	69.2	49.4	54.2	48.0
	Average Density	87.5	62.3	63.6	41.4

Table 9. Analysis of Variance of Volume on the North Freeway

Sources	Sum of Squares	Degrees of Freedom	Mean-Square	F	F Tests $F_{0.20}$	F Tests $F_{0.10}$
Day	23.44	1	23.44	0.11	1.78	2.71
RD	217.51	3	72.50	0.37	1.61	2.08
PD	581.85	3	193.95	0.98	1.61	2.08
LD	375.03	2	187.51	0.95	1.70	2.30
RPD	2926.03	9	325.11	1.64	1.39	1.63
RLD	1334.68	6	222.45	1.12	1.46	1.77
PLD	1539.83	6	256.65	1.30	1.46	1.77
RPLD	4563.98	18	253.55	1.28	1.20	1.43
T(RPLD)	170933.91	864	197.84			
Lane	22706.23	2	11353.12	57.23	1.70	2.30
LD + RLD + PLD + E	174183.45	878	198.39			
Position	23576.87	3	7858.96	39.62	1.61	2.08
PD + LD + RLD + PLD + E	174765.30	881	198.37			
Ramp	2407.01	3	802.34	4.05	1.61	2.08
RD + PD + LD + RLD + PLD + E	174982.81	884	197.94			
RPL	57648.41	18	3202.69	12.63	1.53	1.82
RPLD	4563.98	18	253.55			
PL	24031.24	6	4005.21	20.20	1.46	1.77
PLD + E	172473.74	870	198.24			
RL	102571.84	6	17095.31	86.16	1.46	1.77
RLD + PLD + E	173808.42	876	198.41			
RP	28443.74	9	3160.42	9.72	1.76	2.44
RPD	2926.03	9	325.11			

Table 10. Analysis of Variance of Speed on the North Freeway

Sources	Sum of Squares	Degrees of Freedom	Mean-Square	F	F Tests $F_{0.20}$	F Tests $F_{0.10}$
Day	2442.33	1	2442.33	32.60	1.78	2.71
RD	1865.52	3	621.84	8.30	1.61	2.08
PD	373.19	3	124.40	1.66	1.61	2.08
LD	172.13	2	89.49	1.19	1.70	2.30
RPD	441.76	9	49.09	0.65	1.39	1.63
RLD	9252.51	6	1542.09	20.52	1.46	1.77
PLD	172.13	6	28.69	0.38	1.46	1.77
RPLD	648.59	18	36.03	0.47	1.20	1.43
T(RPLD)	65910.52	864	76.29			
Lane	24729.48	2	12364.74	165.06	1.70	2.30
LD + RPD + PLD + RPLD + E	67345.17	899	74.91			
Position	1895.13	3	631.71	5.08	3.03	5.39
PD	373.19	3	124.40			
Ramp	3216.19	3	1072.06	1.72	3.03	5.39
RD	1865.52	3	621.84			
RPL	2690.68	18	149.48	1.98	1.20	1.43
RPLD + E	66559.11	882	75.46			
PL	730.28	6	121.71	1.62	1.46	1.77
PLD + RPLD + E	66731.24	888	75.15			
RL	9910.20	6	1651.70	7.69	2.20	3.05
RLD	1334.68	6	222.45			
RP	446.50	9	49.61	0.66	1.39	1.63
RPD + PLD + RPLD + E	67173.00	897	74.89			

Duncan's Tests

Using Duncan's Multiple Range and Multiple F Tests it is possible to determine which of the terms in the interaction are significant and which of the variables within these terms are significantly different (13). It is also possible to give the variables a rank order, that is, determine the highest, lowest, and intermediate values. Duncan's test was used to carry out a further analysis of the ramp-position and ramp-position-lane interaction terms.

In carrying out the analysis of variance of the data, the ten and twenty per cent levels of significance were used for testing the variables. When a term is referred to as being significant in this thesis, this means the term is significant at approximately the ten per cent level.

Freeway Volumes

Comparison of Volumes at Different Positions Under Each Ramp Condition

When considering all lanes together as shown in Figure 9 the volumes which occur at North Avenue and Fifth Street are not significantly different from each other under any of the ramp conditions. With the Tenth Street northbound on-ramp closed, the volumes which occur at North Avenue, Fifth Street, and Tenth Street are not significantly different from each other. The volumes which occur at Fourteenth Street are significantly different from each of the other positions. With the North Avenue or the Fourteenth Street on-ramp closed the volumes which occur at Tenth Street and Fourteenth Street are significantly different from

each other and from the volumes at North Avenue and Fifth Street. Under normal operation the volumes at Tenth and Fourteenth Streets are not significantly different from each other but are significantly different from North Avenue and Fifth Street.

Under normal operation the rank order of the positions in volume from the lowest volume to the highest was found to be: Fifth Street and North Avenue first in any order and then Fourteenth Street and Tenth Street in any order. With the North Avenue on-ramp closed the rank order would be North Avenue and Fifth Street first in any order and then Tenth Street and Fourteenth Street. With the Tenth Street on-ramp closed the order would be: Tenth Street, Fifth Street and North Avenue second in any order, and then Fourteenth Street. With the Fourteenth Street on-ramp closed the order would be Fifth Street and North Avenue first in any order and then Fourteenth Street. One must remember that even though there are differences in the means of the volumes which allows one to rank them, these differences may not be significant.

Comparison of Volumes at Each Position Under All Ramp Conditions

When considering all of the ramp conditions together as shown in Figure 10 the volumes at North Avenue and Tenth Street are not significantly different from each other and from the other positions. The rank order of the positions in this case would be: Fifth Street first, North Avenue and Tenth Street second in any order, and then Fourteenth Street.

Comparison of Volumes Under Each Ramp Condition at Different Positions

When comparing the influence of ramp conditions on volume at each of the study locations as shown in Figure 9, the following

information is available. The volume at North Avenue and Fifth Street with the Fourteenth Street on-ramp closed are significantly different from all other ramp conditions. The volumes at North Avenue and Fifth Street under all other ramp conditions are not significantly different from each other. The rank order at North Avenue and Fifth Street would be Fourteenth Street on-ramp closed first and then the other ramp conditions in any order, since they are not significantly different from each other.

The volumes at Tenth Street under normal operation are significantly different from all other ramp conditions. The volumes with the North Avenue on-ramp closed and the Fourteenth Street on-ramp closed are not significantly different from each other. The volumes with the Tenth Street on-ramp closed and the Fourteenth Street on-ramp closed are not significantly different from each other. The rank order at Tenth Street would be Tenth Street on-ramp closed, Fourteenth Street on-ramp closed, and North Avenue on-ramp closed in any order, and then normal operation. The volumes at Fourteenth Street are not significantly different under any of the ramp conditions.

Comparison of Volumes Under Each Ramp Condition Considering All Positions

Considering all of the positions together as shown in Figure 10 the volumes with the North Avenue on-ramp closed are not significantly different from the volumes with the Tenth Street on-ramp closed or the volumes with normal operation. The volumes with the Tenth Street on-ramp closed are not significantly different from the volumes with the Fourteenth Street on-ramp closed. The rank order for the ramp conditions

in this case would be Fourteenth Street on-ramp closed, Tenth Street on-ramp closed, North Avenue on-ramp closed, and normal operation. Only the relative position of the North Avenue on-ramp closure and normal operation can be interchanged in this case. One can see that normal operation of the freeway will give significantly higher volumes when considering all positions together.

Lane Usage at a Non-Interchange Location

When considering the lane usage which occurs at different locations under different ramp conditions on the freeway many interesting facts present themselves. Figures 11, 12, 13, and 14 show the graphs of the ramp-position-lane interaction terms for volumes, speed, and density. The data collected at Fifth Street as shown in Figure 12 gives information about lane usage at a non-interchange (i.e., grade separation) location under different ramp conditions. The volume in lane one is not significantly different under any of the ramp conditions except the Fourteenth Street on-ramp closing. The volume in this case is significantly lower than with any other ramp condition. The volume in lane two is significantly different only when comparing the volume with the Tenth Street on-ramp closed. The lowest significant volume in lane two again occurs with the Fourteenth Street on-ramp closed. There are no significant differences in the volumes in lane three at Fifth Street under any of the ramp conditions. None of the ramp conditions have changed the distribution of vehicles across the three lanes except the North Avenue on-ramp closing and this closure has apparently created a more equal distribution across the three lanes.

Lane Usage at Interchange Locations with Ramps Open

Studying the conditions at North Avenue, Tenth Street, and Fourteenth Street, as shown in Figures 11, 13, and 14, will give an indication of the effect of ramp closure on lane volumes at other interchanges. The volume in lane one at North Avenue is not significantly different under any of the ramp conditions except the Fourteenth Street on-ramp closure. The volume in this case is significantly lower than that with any other ramp condition. The volume in lane two under the North Avenue on-ramp closure is significantly different from all the other ramp conditions. The volume in lane three is not significantly different under any of the ramp conditions.

The volume in lane one at Tenth Street is significantly different only when the Tenth Street on-ramp is closed and then it is significantly lower than the volume with all other ramp conditions. In lanes two and three the volumes are significantly different from normal operation under all ramp conditions except when the Tenth Street on-ramp is closed.

The volume in lane one at Fourteenth Street is significantly different from normal operation under all ramp closure conditions and is significantly lower under normal operation. The volumes in lanes two and three with the Tenth Street on-ramp closed are significantly different from all other ramp conditions except the Fourteenth Street on-ramp closure.

Figure 14 shows that when the North Avenue on-ramp or the Tenth Street on-ramps were closed the volumes in lane one at Fourteenth Street increased significantly while the volumes in lanes two and three

decreased significantly from the volumes with normal operation. Studying the volumes at North Avenue shows that when the Tenth Street on-ramp is closed there is no significant difference in the volume in lane one. When the Fourteenth Street on-ramp is closed there is a significant decrease in the volume in lane one at North Avenue. There is no significant difference in the volumes in lanes two and three at North Avenue under any of the ramp conditions. These facts would seem to indicate that closing a particular ramp would increase the volume of traffic on the freeway in lane one ahead of the next on-ramp, while the volumes in lanes two and three would decrease or remain unchanged. The volumes which occur at Fifth Street also seem to support these indications.

Lane Usage at Closed Interchange Locations

Studying the volumes in all three lanes at North Avenue, Tenth Street, and Fourteenth Street as shown in Figures 11, 13, and 14 when each of these ramps is closed will give an indication of the effect of closing a ramp on the lane usage in the vicinity of the ramp that is closed.

The volumes which occur in lanes one and three at North Avenue with the North Avenue on-ramp closed are not significantly different from the volumes which occur with the freeway operating normally. The volumes in lane two at North Avenue are significantly different when the freeway is operating normally and the North Avenue on-ramp is closed.

The volumes in lanes two and three at Tenth Street with normal operation are not significantly different from the volumes with the Tenth

Street on-ramp closed. The volume in lane one with the Tenth Street on-ramp closed is significantly lower than the volumes with normal operation.

The volumes in lanes two and three at Fourteenth Street with normal operation are not significantly different from the volumes with the Fourteenth Street on-ramp closed. The volume in lane one with the Fourteenth Street on-ramp closed is significantly higher than the volumes with normal operation. These facts seem to indicate that the volumes in all of the lanes remain the same or decrease when compared to normal operation in the vicinity of the ramp that is closed and do not regain their usual volumes until the next on-ramp is reached.

Freeway Speeds

Comparison of Speeds at Different Positions Under Each Ramp Condition

When considering the average speed across the three lanes as shown in Figure 9 under normal operation the speeds which occur at North Avenue and Fifth Street are significantly different from each other and from the other positions. The speeds at Tenth and Fourteenth Street are not significantly different from each other under normal operation of the freeway. The rank order would be Fourteenth Street and Tenth Street in any order, and then Fifth Street, and North Avenue.

With the North Avenue on-ramp closed the speeds which occur at Fifth Street and Fourteenth Street are significantly different from each other and from all the other positions. The speeds at Tenth Street and North Avenue are not significantly different from each

other. The rank order would be Fourteenth Street, Tenth Street and North Avenue in any order, and then Fifth Street.

With the Tenth Street on-ramp closed the speeds at North Avenue and Fifth Street are not significantly different from each other and the speeds at Tenth and Fourteenth Street are not significantly different from each other, but these two pairs of locations are significantly different from each other. The rank order would Fourteenth Street and Tenth Street in any order, and then Fifth Street and North Avenue in any order.

With the Fourteenth Street on-ramp closed there is no significant difference in the speeds at North Avenue, Fifth Street, and Tenth Street. There is a significant difference in the speed at Fourteenth Street and the other locations. The rank order would be Fourteenth Street first, and then Tenth Street, Fifth Street, and North Avenue in any order.

The slope of the speed curves shown in Figure 9 have been apparently reduced from normal operation with any one of the northbound on-ramps closed. This reduction in slope indicates a more uniform, smoother flow of traffic on the freeway between positions.

Comparison of Speeds at Each Position Under All Ramp Conditions

When considering all of the ramp conditions together, as shown in Figure 10, the speeds at Fourteenth Street and Tenth Street are significantly different from each other and the other locations. The speeds at North Avenue and Fifth Street are not significantly different from each other. The rank order is Fourteenth Street, Tenth Street, Fifth Street, and North Avenue. Because they are not significantly

different; Fifth Street and North Avenue can be ranked in any order with respect to each other.

Comparison of Speeds Under Each Ramp Condition at Different Positions

When comparing the influence of ramp conditions on speeds at each of the study locations as shown in Figure 9 the following information is available. There is no significant difference in the speeds at North Avenue when the North Avenue, Tenth Street, and Fourteenth Street on-ramps are closed but these speeds under ramp closure conditions are significantly different from normal operation. The rank order would be normal operation first and the other ramp conditions in any order. These differences also hold true for speeds at Fifth Street.

The speeds at Tenth Street under normal operation and with the Tenth Street on-ramp closed are significantly different from each other and from all other ramp conditions. The speeds at Tenth Street with the Fourteenth Street on-ramp closed and the Tenth Street on-ramp closed are not significantly different from each other. The rank order is normal operation, Tenth Street on-ramp closed, and then North Avenue and Fourteenth Street on-ramp closed in any order.

The speeds at Fourteenth Street under normal operation and with the Fourteenth Street on-ramp closed are significantly different from each other and from all other ramp conditions. The speeds at Fourteenth Street with the Tenth Street on-ramp closed and the North Avenue on-ramp closed are not significantly different from each other. The rank order in this case is normal operation first, and then Tenth Street and North Avenue on-ramp closed in any order, and then Fourteenth Street on-ramp closed.

Comparison of Speeds Under Each Ramp Condition Considering All Positions

Considering all of the positions together as shown in Figure 10 the speeds with normal operation are significantly different from all other ramp conditions and the ramp closure conditions are not significantly different from each other. The rank order would be normal operation first, and the other ramp conditions in any order. One can see that closing any one of the on-ramps at North Avenue, Tenth Street, or Fourteenth Street will significantly increase the speed of the traffic on the North Freeway.

Lane Speeds at a Non-Interchange Location

Studying the speeds at Fifth Street as shown in Figure 12 will give information about the effect of ramp closures on speeds at a non-interchange location. The speeds in all three lanes with normal operation are significantly different from all other ramp conditions, but the speeds in all three lanes for all other ramp conditions are not significantly different from each other. Significantly lower speeds occur in all three lanes with normal operation of the freeway while significantly higher speeds occur with all other ramp conditions.

Lane Speeds at Interchange Locations with Ramps Open

Studying the conditions at North Avenue, Tenth Street, and Fourteenth Street as shown in Figures 11, 13, and 14 when these ramps are either opened or closed will give an indication of the effect of ramp closures on speeds at these interchanges. Comparison of the respective lanes at North Avenue shows that there is no significant difference in the speeds in any of the three lanes under any of the

ramp conditions. At Tenth Street there is a significant difference in the speeds between normal operation and all other ramp conditions in all three lanes; however there is no significant difference in the speeds in the respective lanes at Tenth Street between the ramp closure conditions. The rank order at Tenth Street would be normal operation first, and the remaining ramp conditions in any order because there is no significant difference in them.

The speeds at Fourteenth Street in lane one with the Fourteenth Street on-ramp closed and normal operation are significantly different from each other and the other ramp conditions; however the speeds for the other ramp conditions are not significantly different from each other. The speeds in lanes two and three with normal operation are significantly different from speeds obtained for the other ramp conditions, but the speeds obtained for ramp closure conditions are not significantly different from each other.

One can see by studying Figure 11 that the speeds in all three lanes at North Avenue are not changed significantly by any of the ramp conditions. The speeds in all of the lanes at Fifth Street have changed significantly from those obtained with normal operation by all of the ramp closures, but the speeds are not significantly different between the ramp closures. The same differences were found at Tenth Street that existed at Fifth Street. The speeds at Fourteenth Street with the North Avenue on-ramp closed, the Tenth Street on-ramp closed, and the Fourteenth Street on-ramp closed were significantly higher than the speeds with normal operation.

The relative rank of speeds in the lanes remains the same at all locations under all ramp conditions with the exception of the rank of the speeds in the lanes at Fourteenth Street with the Fourteenth Street on-ramp closed. The rank of the speeds in the lanes at Fourteenth Street from the lowest to the highest with normal operation is: lane one, lane two, and lane three. When the Fourteenth Street on-ramp is closed the order is reversed with lane one having the highest speed. This particular characteristic is not exhibited at any of the other interchanges.

Lane Speeds at Closed Interchange Locations

Studying the speeds in all three lanes at North Avenue, Tenth Street, and Fourteenth Street as shown in Figures 11, 13, and 14 when each of these ramps is closed will give an indication of the effect of closing a ramp on the speeds in each lane in the vicinity of the ramp that is closed.

The speeds in all three lanes at North Avenue with normal operation are not significantly different from the speeds with the North Avenue on-ramp closed.

The speeds in all three lanes at Tenth Street with normal operation are significantly lower than the speeds with the Tenth Street on-ramp closed.

The speeds in all three lanes at Fourteenth Street with normal operation are significantly lower than the speeds with the Fourteenth on-ramp closed.

The speeds in all three lanes at North Avenue, Tenth Street, and Fourteenth Street with normal operation are generally significantly

lower than the speeds which occur when the on-ramp at these locations are closed.

Freeway Density

Comparison of Densities at Different Positions Under Each Ramp Condition

When considering all lanes together as shown in Figure 9 with the freeway operating normally the density at all of the positions are significantly different from each other. The rank order is North Avenue, Fifth Street, Tenth Street, and Fourteenth Street.

The density on the freeway is not significantly different between any of the positions with the Fourteenth Street on-ramp closed. The positions can be ranked in any order.

The densities at North Avenue and Tenth Street with the Tenth Street on-ramp closed are not significantly different from each other but are significantly different from the density at Fourteenth Street. The density at Fifth Street with the Tenth Street on-ramp closed is not significantly different from the density at North Avenue, but is significantly different from the density at Tenth Street. The rank order would be Fifth Street and North Avenue first in any order, and then Tenth Street and Fourteenth Street.

When the North Avenue on-ramp is closed the densities at North Avenue and Fifth Street are not significantly different from each other; however the densities at Tenth Street and Fourteenth Street are significantly different from each other and the other locations. The rank order of the positions with the Tenth Street on-ramp closed would be Fifth Street, North Avenue, Tenth Street, and Fourteenth Street. The rank order of the positions with the North Avenue on-ramp closed is Fifth Street and North Avenue first in any order, and then Tenth Street and Fourteenth Street.

Table 11. Analysis of Variance of Density on the North Freeway

Sources	Sum of Squares	Degrees of Freedom	Mean Square	F	F Tests $F_{0.20}$	F Tests $F_{0.10}$
Day	8324.40	1	8334.40	19.95	1.78	2.71
RD	9179.77	3	3059.92	7.32	1.61	2.08
PD	874.79	3	291.60	0.70	1.61	2.08
LD	1750.25	2	875.13	2.09	1.70	2.30
RPD	6104.94	9	678.33	1.62	1.39	1.63
RLD	35180.67	6	5863.44	14.02	1.46	1.77
PLD	2431.78	6	405.30	0.97	1.46	1.77
RPLD	11429.47	18	634.97	1.52	1.20	1.43
T(RPLD)	361417.68	864	418.31			
Lane	122107.44	2	61053.72	69.76	5.00	9.00
LD	1750.25	2	875.13			
Position	21953.76	3	7317.92	17.52	1.61	2.08
PD + PLD + E	364724.25	873	417.78			
Ramp	23533.42	3	7844.47	2.56	3.03	5.39
RD	9179.77	3	3059.92			
RPL	47465.80	18	2636.99	4.15	1.53	1.82
RPLD	11429.47	18	634.97			
PL	16656.07	6	2776.01	6.64	1.46	1.77
PLD + E	363849.46	870	418.22			
RL	106363.37	6	17727.23	3.02	2.20	3.05
RLD	35180.67	6	5863.44			
RP	12723.35	9	1413.71	2.08	1.76	2.44
RPD	6104.94	9	678.33			

Comparison of Densities at Each Position Under All Ramp Conditions

When all of the ramp conditions are considered together as shown in Figure 10 the densities at North Avenue and Fifth Street are not significantly different from each other, but are significantly different from the other ramp conditions. The densities at Tenth Street and Fourteenth Street are significantly different from each other and from the other locations. The rank order would be North Avenue and Fifth Street first in any order, and then Tenth Street and Fourteenth Street.

Comparison of Densities Under Each Ramp Condition at Different Positions

Considering the average density in the three lanes as shown in Figure 9 there is no significant difference in the density at North Avenue under any of the ramp conditions. The densities at Fifth Street and Tenth Street are not significantly different between the ramp closure conditions, but all of the ramp closure conditions have significantly lower densities than the densities obtained with normal operation. The densities at Fourteenth Street which occur with the North Avenue on-ramp closed and the Tenth Street on-ramp closed are not significantly different from each other, but are significantly different from the other ramp conditions. The rank order at Fourteenth Street would be Fourteenth Street on-ramp closed first, and then North Avenue on-ramp and Tenth Street on-ramp closed in any order, and then normal operation.

The slope of the density curves shown in Figure 9 have apparently been reduced from normal operation with any one of the northbound on-ramps closed. This reduction in slope indicates a more uniform, smoother flow of traffic between positions with all ramps closed. The

greatest reduction in the slope of the density curve occurs with the Fourteenth Street northbound on-ramp closed.

Comparison of Densities Under Each Ramp Condition Considering All Positions

Considering all of the positions together as shown in Figure 10 one finds that there is no significant difference in the density on the freeway between the ramp closure conditions; however, the density on the freeway with normal operation is significantly higher than the density with any of the on-ramps closed.

Lane Densities at a Non-Interchange Location

Studying the density at Fifth Street as shown on Figure 12 will give an indication of the effect of ramp conditions on density at a non-interchange location.

The influence of the ramp closings on the density at Fifth Street is similar in all three respective lanes. The density in the three lanes is significantly different only between normal operation and the North Avenue on-ramp closing. There is no significant difference in densities with the other ramp conditions. The rank order is North Avenue on-ramp closed first, and then Tenth Street and Fourteenth Street on-ramp closed in any order, and finally normal operation.

Lane Densities at Interchange Locations with Ramps Open

Studying the density conditions at North Avenue, Tenth Street, and Fourteenth Street as shown in Figures 11, 13, and 14 when these ramps are either opened or closed will give an indication of the effect of ramp closures on densities at these interchanges.

The density at North Avenue in any of the respective lanes is not significantly different under any of the ramp conditions. The density at Tenth Street in lanes one and two with normal operation is significantly different from the density obtained under all other ramp conditions. In lane three at Tenth Street the density with normal operation is significantly different from all other ramp conditions except the Tenth Street on-ramp closing.

The densities at Fourteenth Street in lane one with normal operation and the Fourteenth Street on-ramp closed are significantly differeng from each other and from the other ramp conditions. The densities in lane one with the North Avenue on-ramp closed and the Tenth Street on-ramp closed are not significantly different. The densities at Fourteenth street in lanes two and three with normal operation are significantly different from the densities obtained under all ramp closure conditions. The rank order at Fourteenth Street in all three lanes would be normal operation first, and then the North Avenue and Tenth Street on-ramp closures in any order, and then the Fourteenth Street on-ramp closed.

Studying the density on the North Freeway over all positions and ramp conditions indicates that the greatest influence of closing a ramp generally occurs ahead of the ramp and is reflected by a decrease in density. This fact is verified by the analysis of the data at North Avenue which shows no significant differences in the densities under any of the ramp conditions and the data at Fifth Street which shows a significant difference in densities between normal operation and the

North Avenue on-ramp closure. The Tenth Street and Fourteenth Street on-ramp closings had no significant effect on the density at Fifth Street. This fact indicates that the density is not affected to a great extent prior to the on-ramp which is closed. The data taken at Tenth Street and Fourteenth Street indicate similar results. In all cases significantly lower densities in lane one occurred when the on-ramp at the location being studied was closed. The densities in the three respective lanes were not significantly different from each other at North Avenue and Fifth Street under any of the ramp conditions. The density in lane one at Fourteenth Street was significantly higher than the density in the other two lanes when the North Avenue and the Tenth Street on-ramps were closed. These facts indicate that the motorists who were normally entering the freeway at North Avenue under normal operation entered the freeway at Tenth and Fourteenth Street when the North Avenue on-ramp was closed, thereby creating higher densities in lane one at Fourteenth Street. The same effect would occur at Fourteenth Street and North Avenue when the Tenth Street on-ramp was closed.

Lane Densities at Closed Interchange Locations

Studying the densities in all three respective lanes at North Avenue, Tenth Street, and Fourteenth Street as shown in Figures 11, 13, and 14 when each of these ramps is closed will give an indication of the effect of closing a ramp on the density in each lane in the vicinity of the ramp that is closed.

The densities in all three lanes at North Avenue with normal operation are not significantly different from the density obtained with the North Avenue on-ramp closed.

The densities in all three lanes at Tenth Street with normal operation are significantly higher than the density with the Tenth Street on-ramp closed.

The density in all three lanes at Fourteenth Street with normal operation is significantly higher than the density with the Fourteenth Street on-ramp closed.

Generally the density in all three lanes at the location being studied was significantly lower than normal operation when the on-ramp was closed at the study location.

Volume-Speed Relationship

Figure 15 shows an ideal volume-speed curve which may exist on any freeway (14). This figure illustrates how certain volumes can be obtained on a freeway at various speeds. The top of the curve which is a straight line indicates the speeds at which the traffic would be flowing freely and the lower dashed portion of the curve indicates the speeds at which congestion would exist.

An illustration of how this curve may fit the data presented in this thesis will be given: Studying the volume and speed curves in Figure 9 will show that with the Fourteenth Street northbound on-ramp closed there is a significant difference in the volume and speed at Tenth Street and Fourteenth Street. The volume at Fourteenth Street is significantly higher than at Tenth Street and the speed at Fourteenth Street was significantly lower. Reflection on these statements would lead one to believe that there should be no difference in volume between Tenth Street and Fourteenth Street with the Fourteenth Street on-ramp closed because there is no location for the additional vehicles to enter the traffic stream after passing the Tenth Street northbound on-ramp. If one studies these volume-speed conditions in relation to Figure 15 the

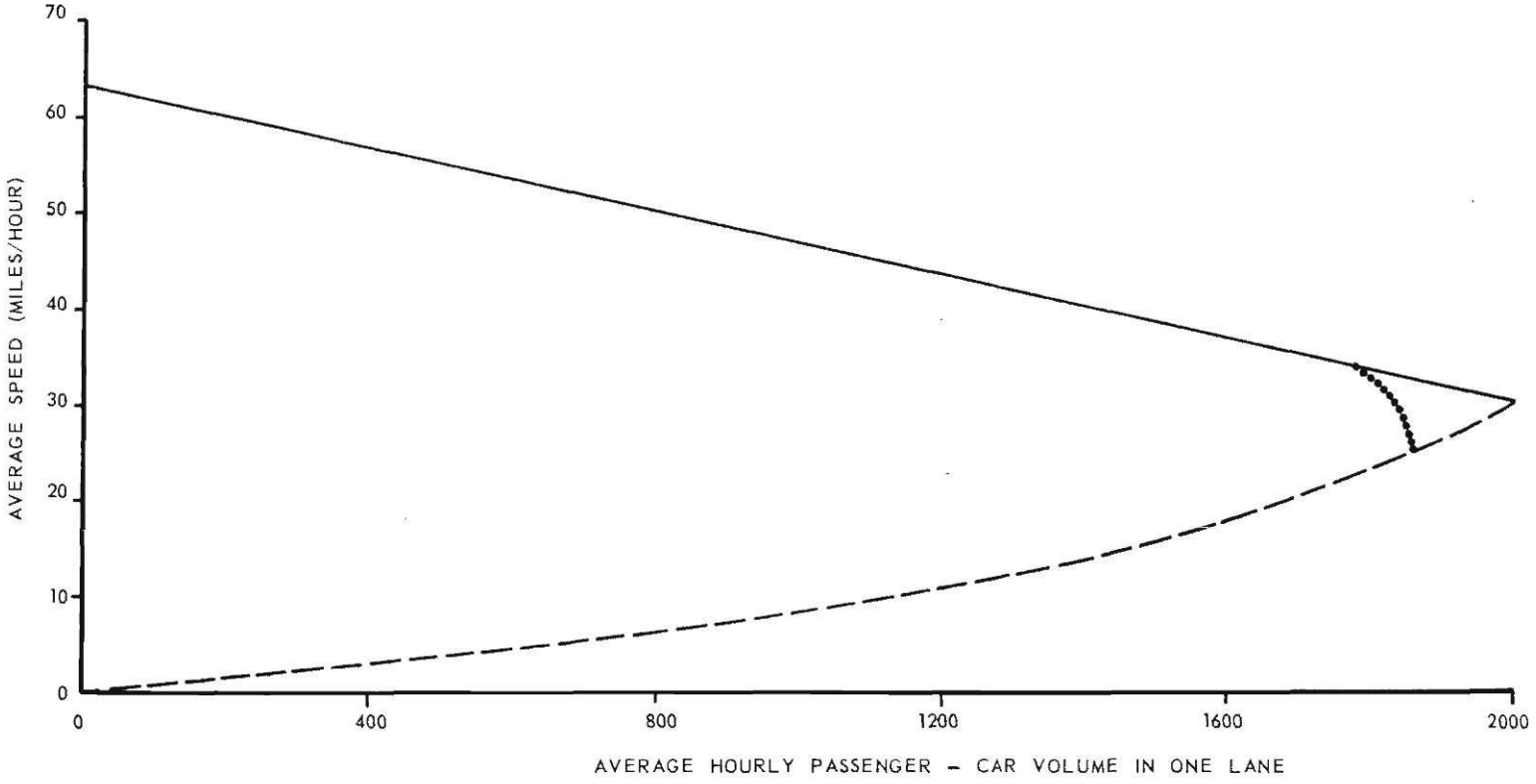

Figure 15. Volume-Speed Curve for Four-Lane Freeways (7).

explanation will become clear. The volume at Tenth Street was approximately 108 vehicles per five minute time interval at an average speed of 40.3 miles per hour. The volume at Fourteenth Street was approximately 125 vehicles per five minute time interval per lane at an average speed of 37.9 miles per hour. Comparing these figures with Figure 15 shows that they lie very close to the ideal volume-speed curve at both points. What has happened between Tenth Street and Fourteenth Street is that the volume has increased and the speed has decreased.

Speed and Delay Study

The overall travel and running speeds on the North Freeway for each of the ramp conditions are shown in Tables 12 and 14, respectively. The analysis of variance of these speeds is shown in Tables 13 and 15. The analysis of variance of these speeds verified the results of the analysis of the speeds computed from the time-lapse movie data. The results of the analysis of variance of the overall travel and running speeds on the North Freeway were similar and show that there is a significant difference in the speeds with the freeway operating normally and the speeds with any one of the on-ramps closed. There are no significant differences in the speeds on the North Freeway when comparing the speeds which occur under ramp closures. The overall travel and running speeds were significantly higher with any one of the on-ramps closed on the freeway than under normal operation.

Total Overall Travel Time

The results of the analysis of variance of the total overall travel time expressed in vehicle-minutes on the North Freeway are shown in Table 16. The results of the analysis of variance show that there is

Table 12. Overall Travel Speed on North Freeway

Day	Travel Speed (Miles per Hour)			
	Normal Operation (All Ramps Open)	North Avenue Northbound On-Ramp Closed	Tenth Street Northbound On-Ramp Closed	Fourteenth Street Northbound On-Ramp Closed
1	30.6	34.8	39.8	40.6
2	26.6	35.6	32.7	36.6
3	29.9	33.1	24.8	35.2
Mean	29.0	34.5	32.4	37.5

Table 13. Analysis of Variance of Overall Travel Speed on North Freeway

Sources	Sum of Squares	Degrees of Freedom	Mean Square	F	F Tests	
					$F_{0.20}$	$F_{0.10}$
Day	66.34	2	33.17	2.68	2.33	3.46
Ramp	113.23	3	37.74	3.05	2.34	3.29
Ramp-Day	74.36	6	12.39			

Table 14. Overall Running Speed on North Freeway

Normal Operation (All Ramps Open)	North Avenue Northbound On-Ramp Closed	Tenth Street Northbound On-Ramp Closed	Fourteenth Street Northbound On-Ramp Closed
30.6	34.8	39.8	40.6
26.6	38.8	32.7	36.6
31.3	33.1	26.8	35.2
29.5	35.6	33.1	37.5

Table 15. Analysis of Variance of Overall Running Speed on North Freeway

Sources	Sum of Squares	Degrees of Freedom	Mean Square	F	F Tests	
					$F_{0.20}$	$F_{0.10}$
Day	47.30	2	23.65	1.71	2.33	3.46
Ramp-Day	83.13	6	13.87			
Ramp	109.50	3	36.50	2.24	2.10	2.92
RD + Day	130.43	8	16.30			

Table 16. Analysis of Variance of Total Overall Travel Time on North Freeway

Sources	Sum of Squares	Degrees of Freedom	Mean Square	F	F Tests $F_{0.20}$	F Tests $F_{0.10}$
Day	16,415,667	2	8,207,834	1.66	2.33	3.46
Ramp-Day	29,652,233	6	4,942,039			
Ramp	48,475,225	3	16,158,408	2.81	2.10	2.92
RD + Day	46,067,900	8	5,758,487			

Table 17. Analysis of Variance of Total Overall Travel Distance on North Freeway

Sources	Sum of Squares	Degrees of Freedom	Mean Square	F	F Tests $F_{0.20}$	F Tests $F_{0.10}$
Day	22,417	2	11,209	7.93	2.33	3.46
Ramp	1,335,059	3	445,020	299.6	2.34	3.29
Ramp-Day	8,925	6	1,488			

a significant difference in the total overall travel time with the freeway operating normally and the total overall travel time on the freeway with any one of the on-ramps closed. There is no significant difference in the total overall travel time on the North Freeway when comparing the total travel time which occurs under ramp closures. The total overall travel time was significantly lower with the Fourteenth Street northbound on-ramp closed than the total overall travel time which occurred under other ramp conditions.

Total Overall Travel Distance

The results of the analysis of variance of the total overall travel distance expressed in vehicle-miles on the North Freeway are shown in Table 17. The results of the analysis of variance show that there is a significant difference in the total overall travel distance on the freeway between all ramp conditions. The rank order of the ramp conditions from the lowest travel distance to the highest is Fourteenth Street on-ramp closed, Tenth Street on-ramp closed, normal operation, and North Avenue on-ramp closed.

CHAPTER V

RESULTS, CONCLUSIONS AND RECOMMENDATIONS

Summary of Results

A summary of the results of the analysis of the data collected on this study can be outlined as follows:

1. Considering all positions, the highest volumes on the North Freeway occurred with the freeway operating normally and the significantly lowest volumes occurred with the Fourteenth Street and Tenth Street northbound on-ramp closed. The volumes obtained with the Tenth Street and Fourteenth Street northbound on-ramps closed were not significantly different from each other.

2. The traffic volumes between the four study locations increased as one moved north on the North Freeway from North Avenue to Fourteenth Street. The rank order of the locations in volume from the lowest to the highest was North Avenue, Fifth Street, Tenth Street, and Fourteenth Street; however, the volumes which occurred at North Avenue and Fifth Street were not significantly different from each other.

3. The speed on the North Freeway decreases significantly under all ramp conditions as one moves north on the freeway from North Avenue to Fourteenth Street. The speeds on the freeway under all conditions of a amp closure were significantly higher than the speeds obtained with the freeway operating normally. There was no significant difference in speeds under ramp closure conditions.

4. The speeds on the North Freeway under all ramp conditions were significantly lower at Fourteenth Street than any of the other positions. The speeds which occurred at North Avenue and Fifth Street were not significantly different from each other under ramp closure conditions but were significantly different under normal operation. The speeds at North Avenue and Fifth Street were significantly higher than the speeds at the other positions under all ramp conditions.

5. The density on the North Freeway generally increases significantly as one moves north on the freeway from North Avenue to Fourteenth Street; however, the density with the Fourteenth Street on-ramp closed is not significantly different between any of the four study locations. Considering all of the positions together, the density on the North Freeway is significantly highest with normal operation. The densities of the freeway with any one of the on-ramps closed are significantly lower than the densities with normal operation, but are not significantly different from each other.

6. The relative relationship of the speeds in the respective three lanes to each other was apparently not changed significantly with any of the ramps closed from the relationship that existed with normal operation. The speeds in each of the respective three lanes were significantly higher than normal operation with any of the ramps closed at all the study locations, with the exception of the speeds in the three lanes at Fourteenth Street with the Fourteenth Street on-ramp closed, in which case the relative order of the speeds in the three lanes was reversed.

7. The densities which occur on the freeway under different ramp conditions indicate that closing any of the on-ramps on the freeway does not affect the density on the freeway prior to the ramp that is closed.

8. The speed and delay study made on the North Freeway verified the results of the data collected on the freeway by time-lapse movie photography at the four study locations. The speeds on the freeway were significantly higher with the Fourteenth Street on-ramp closure than with any of the other ramp conditions. The speeds on the freeway under all ramp conditions except the Fourteenth Street on-ramp closure were not significantly different from each other.

9. The total overall travel time expressed in vehicle-minutes on the North Freeway with the Fourteenth Street on-ramp closed was significantly lower than the total travel time on the freeway under any other ramp condition. The total overall travel times on the freeway under all ramp conditions except the Fourteenth Street on-ramp closure were not significantly different from each other.

10. The total overall travel distance expressed in vehicle-miles on the North Freeway with the Fourteenth Street on-ramp closed was significantly lower than the total travel distance on the freeway under any other ramp condition. The total overall travel distances on the freeway under all ramp conditions except the Fourteenth Street on-ramp closure were not significantly different from each other.

11. Closing any one of the northbound on-ramps to the North Freeway at North Avenue, Tenth Street, and Fourteenth Street resulted in a more uniform, smoother flow of traffic as reflected by the speeds

and densities on the freeway. The speed and density were more uniform between positions when any one of the on-ramps was closed than when the freeway was operating normally.

Conclusions

The following conclusions were reached after a careful evaluation of the results of the data analysis.

1. An effective measure of the level of service which exists in a system of freeways is the total overall vehicle-minutes of travel time used by all the vehicles traveling through the freeway system during a specified time period, usually the peak hour of traffic flow.

2. Studying the volume, speed, and density on a freeway at several different locations simultaneously with variable ramp spacings will give a more reliable indication of the true traffic flow characteristics which exist on the freeway under variable ramp spacings than a point study at the particular interchange where the ramp is closed.

3. Closing any one of the northbound on-ramps on the North Freeway at North Avenue, Tenth Street, and Fourteenth Street during the afternoon peak hour will improve the overall operating characteristics of the traffic on the North Freeway. This improvement is shown by the smoother, more uniform flow of traffic as reflected by the speeds and densities on the freeway.

4. The reasons for the increased speeds on the freeway with any one of the on-ramps closed is apparently caused by the following factors:

a. Elimination of the short weaving section on the North Freeway between Fourteenth Street and the junction of the Northeast and Northwest Freeways by closing the northbound on-ramp at Fourteenth Street.

b. Removal of intersection conflict when the on-ramps are closed.

c. "Metering" the flow of traffic entering the freeway by reducing the number of ingress points. When any one of the on-ramps to the freeway is closed this effectively reduces the number of vehicles entering the freeway because the capacity of the ramps that remain open is constant.

5. Problems of congestion, delay, and accidents may be created on the arterial street system serving the freeway when any one of the on-ramps is closed.

Recommendations

The following recommendations are made as a result of the findings of this study.

1. Considering the operation of the freeway, it is recommended that interchanges be spaced as far apart as possible consistent with the effective operation of the freeway and the arterial street system serving the freeway.

2. It is recommended that the Fourteenth Street northbound on-ramp be closed during the afternoon peak period of traffic flow from 4:30 P. M. to 6:00 P. M. for a test period of three months and that further extensive tests be carried out on a system basis to determine whether the Fourteenth Street northbound on-ramp should be closed during these hours on a permanent basis. Overall improvement of the traffic flow characteristics on the freeway and arterial street system should

be used as a criterion for closing the northbound on-ramp at Fourteenth Street permanently.

It is recommended that in designing all future freeways, serious consideration be given to the possibility of designing interchanges on the freeways so that these interchanges will function during the off-peak hours only and will be closed to traffic during the peak period of traffic flow.

4. In making any further studies of this nature it is recommended that the study be made on both a system and sub-system basis. This means that studies should be made on the freeway and the city streets serving the freeway.

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